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THE "φ-DETECTOR", A DETECTOR VALVE FOR FREQUENCY MODULATION

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With frequency modulation a much lower level of noise and other interference can be reached than with the method of amplitude modulation hitherto more commonly used. Frequency modulation is therefore being applied more and more, although it is limited to transmitters working on very short waves (at most a few metres). In the United States of America dozens of broadcasting transmitters are already working according to this method of modulation. It has even been laid down there that frequency modulation is to be used for the transmission of sound in television. A description is given of a new valve with which a frequency-modulation detector can be built possessing very good detection properties. Moreover with this valve the system can be greatly simplified, since it takes the place of several circuits and valves needed in other systems. Between the cathode and the anode this valve has seven grids.

An important advantage of telecommunication by means of carriers modulated in frequency instead of in amplitude lies in the fact that, given a well constructed transmitter and receiver, there is little interference in reception due to noise, to signals of other transmitters and to impulse-like interference.

As Armstrong showed in 1936[1]), in order to get this high degree of freedom from interference the transmitter should work with a frequency sweep which is great compared with the highest modulation frequency[2]). Moreover the receiver should be of such a construction that variations in the amplitude of the signal applied to the detector do not cause any appreciable a.f. voltage.

The circuits applied in good receivers for frequency modulation answer this requirement but are rather complicated. Here a new valve is described which allows of much simpler circuits and, as will be shown, moreover offers other advantages.

First of all we shall briefly consider the functioning of a detector for frequency modulation (FM-detector).

Functioning of an FM-detector

In *fig. 1* a block diagram is given representing a superheterodyne receiver for frequency modulation. The intermediate frequency f_i, obtained by mixing the (amplified) aerial signal with an oscillator voltage (constant frequency f_o), shows the same variations corresponding to the modulation as does the frequency f_t of the aerial signal. The central frequency at present usually chosen for the i.f. amplifier is about 10 Mc/s.

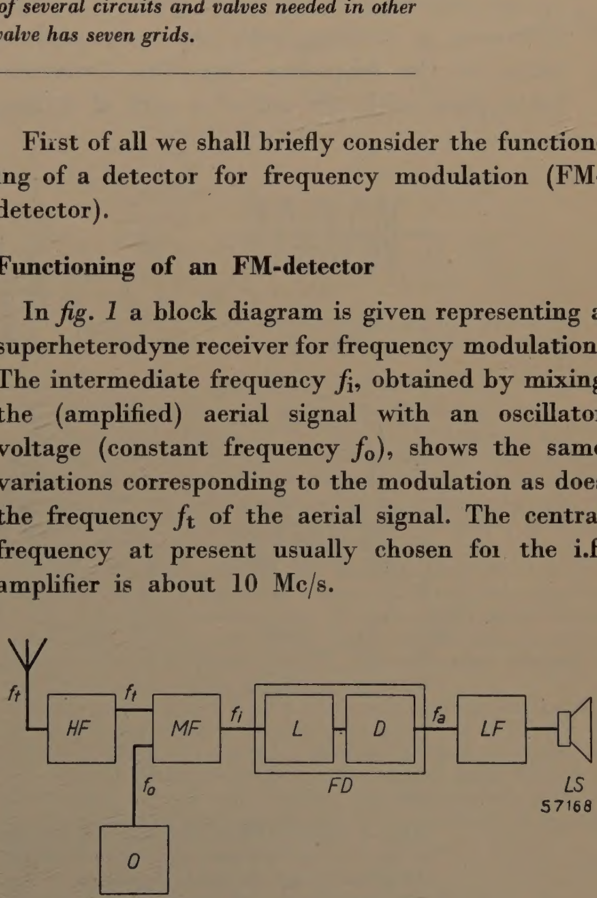

Fig. 1. Block diagram of a frequency-modulation receiver. HF = high-frequency amplifier, O = oscillator, MF = intermediate-frequency amplifier, FD = frequency-modulation detector with the limiter L and the discriminator D, LF = audio-frequency amplifier, LS = loudspeaker. f_t = frequency of the transmitter, f_o = oscillator frequency, $f_i = f_t - f_o$ = intermediate frequency, f_a = audio-frequency.

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1) E. H. Armstrong, A method of reducing disturbances in radio-signaling by a system of frequency modulation, Proc. Inst. Rad. Engrs. 24, 689-740, 1936.

2) By frequency sweep is understood the largest deviation from the central frequency, i.e. the frequency of the transmitter in the absence of modulation; see e.g. Th. J. Weijers, Frequency modulation, Philips Techn. Rev. 8, 42-50, 1946.

The frequency detector has two functions: that of a limiter (performed by the part L, fig. 1) which renders the amplitude variations just mentioned innocuous, and that of frequency discriminator (part D). We shall first consider the latter.

Frequency discrimination

In the main two methods of frequency discrimination are known:

a) The frequency fluctuations are converted into amplitude variations which are detected in the familiar manner (*fig. 2a*). Conversion is brought about with the aid of a network the impedance of which depends upon the frequency; detection (rectifying) is done by one or more diodes. This network may in principle consist of a simple LC circuit, but usually it is a system of two or three coupled circuits (band-pass filter). This gives a better approximation to a linear relation between the variations of frequency and amplitude, so that there is less distortion.

b) From the received signal two voltages (v_1 and v_2) are derived between which there is a phase difference φ varying with the instantaneous value of the frequency (fig. 2*b*). Detection takes place with the aid of a sort of mixing valve with two control grids to which the voltages v_1 and v_2 are applied. This method, which hitherto has been employed much less than that under (a), will be reverted to in more detail farther on.

Limitation

The voltage at the output of the i.f. amplifier, thus the voltage that is applied to the frequency detector, would be expected to have a constant amplitude, since every endeavour is made in the transmitter to keep the signal transmitted as free of amplitude modulation as is possible. There are, however, a number of causes that can be indicated whereby the said output voltage may be amplitude modulated to a fairly great depth. These causes are the following.

Even though a transmitter may be working with a perfectly constant amplitude, the signal received by the receiver aerial need not by any means be constant: inter-action between the waves reaching the receiver aerial along different paths and dispersion in the atmosphere may cause considerable amplitude modulation in the received signal, this modulation being found again at the output of the i.f. amplifier.

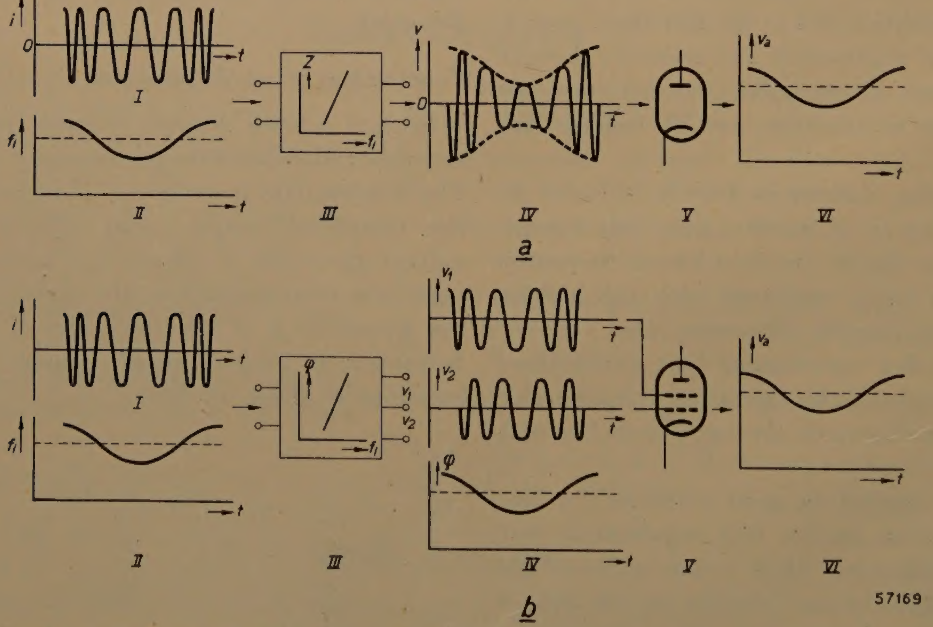

Fig. 2. Two methods of frequency discrimination.

a) At I a frequency-modulated current i and at II the instantaneous value of the frequency f_i are shown as functions of the time t. The current traverses a network (III), the impedance Z of which is linearly dependent upon f_i. Across the network there then arises an a.m. voltage v (IV) which with the aid of one or more diodes (V) is rectified to the a.f. voltage v_a (VI).

b) According to another method the current i (see I) is conducted through a network (III) which yields two voltages v_1 and v_2 between which there is a phase difference φ linearly dependent upon f_i. At IV v_1, v_2 and φ are shown as a function of t. v_1 and v_2 are each applied to a control grid of a kind of mixing valve (V) of which the output voltage v_a varies with the modulation frequency (VI).

Furthermore, interfering signals also cause amplitude variations. These may arise both from undesired stations and, for instance, from the ignition of passing motor vehicles, as well as from noise sources (principally the first valve in the receiver).

Finally, another source of amplitude modulation lies in the i.f. transformer at the output side of the i.f. amplifier. The ideal solution would be a band-pass filter with a rectangular frequency characteristic, i.e. a filter passing a frequency band of the desired width absolutely uniformly. In practice, however, one is content with a filter the characteristic of which has, for instance, the shape represented in *fig. 3*, curve *I*. The sweep of the intermediate frequency (curve *II*) results in the amplitude of the output voltage being modulated (curve *III*). As the illustration shows, this modulation is distorted; when detected, it would give rise to a more or less distorted reproduction.

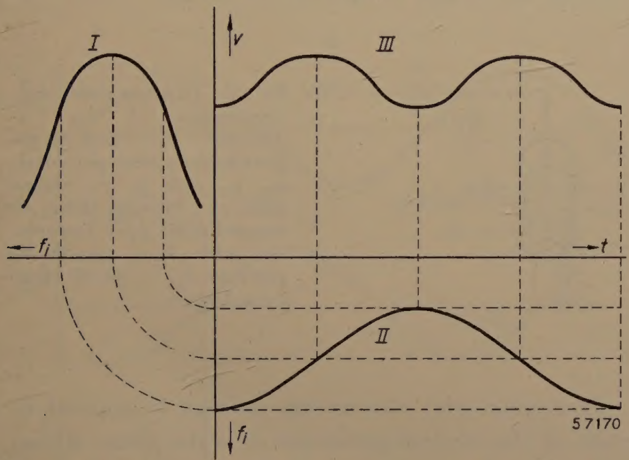

Fig. 3. I= resonance curve of an i.f. transformer: voltage V as a function of the frequency f_i. When f_i varies sinusoidally with the time (curve II) then V shows a distorted amplitude modulation (curve III).

It is now the task of the limiter to prevent the amplitude variations in the output voltage of the i.f. amplifier penetrating into the frequency discriminator. The use of a limiter not only suppresses noise and other interference but at the same time considerably attenuates the distortion just referred to.

Fig. 4 gives a diagrammatic representation of some known limiting systems with a brief explanation.

A frequently used circuit for frequency detection

Amplitude limitation can be combined with both the systems of frequency discrimination mentioned above under (a) and (b). *Fig. 5* represents a much used circuit where the limiter corresponds to that of fig. 4*a* and frequency discrimination is performed by the method given under (a). The frequency fluctuations here produce amplitude variations in a manner described by Foster and Seeley and already discussed in this journal [3]).

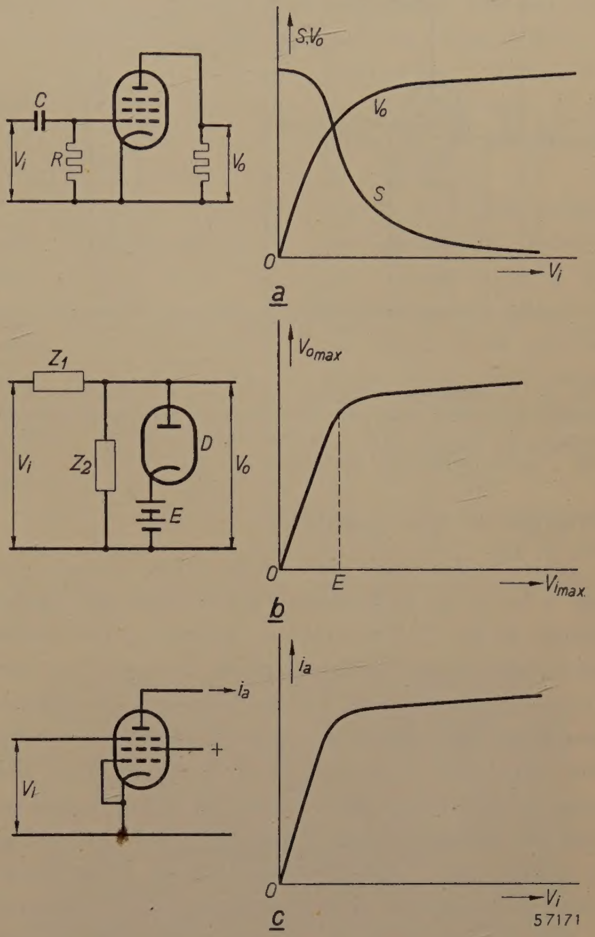

Fig. 4. Three methods of amplitude limitation.
a) Grid detection arises by the grid capacitor C and the leak resistor R, so that the grid voltage becomes more strongly negative as the signal V_i increases. At the same time, however, the slope S of the pentode drops, in such a way as to cause the output voltage V_o to remain practically constant (provided V_i is large enough).
b) Connected in parallel with the impedance Z_2 is a diode D in series with a threshold voltage E. When the amplitude $V_{i\,\mathrm{max}}$ of the input signal exceeds the value E the diode becomes conducting and the amplitude $V_{o\,\mathrm{max}}$ of the output voltage cannot rise much higher than E. The difference between V_i and V_o is taken up by the impedance Z_1.
c) The anode current i_a of a valve is practically independent of the voltage V_i at a control grid (provided V_i is not too small) if inside this control grid there are one or more grids at constant potential screening the control grid. If V_i is an alternating voltage with varying but continuously sufficient amplitude, then the amplitude of i_a remains practically constant.

The "φ-detector", the new valve that we are about to discuss, in its function as frequency discriminator comes under (b): detection of phase differences. At the same time it acts as amplitude limiter, according to the diagram of fig. 4c. Thus the two functions are combined in one valve.

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[3]) D. E. Foster and S. W. Seeley, Proc. Inst. Rad. Engrs. **25**, 289-313, 1937. See also the article quoted in footnote [2]), in particular figs 10, 11 and 12 and accompanying text.

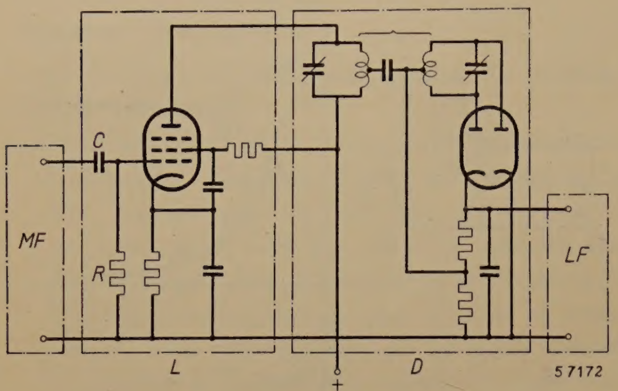

Fig. 5. A commonly used circuit for an FM detector. L = limiter according to fig. 4*a*, D = frequency discriminator according to fig. 2*a*. MF = intermediate-frequency amplifier, LF = audio-frequency amplifier.

Principle of the "φ-detector"

The "φ-detector" has seven grids, denoted in *fig. 6* by g_1-g_7 and shown separately in the photograph of *fig. 7*. The grids g_2, g_4 and g_6 are screen grids which provide a screening between the two control grids (g_3 and g_5) and between these grids and the other electrodes, and to which a constant, low, positive voltage (20 V) has to be applied. The innermost grid g_1 likewise has a constant potential, for instance that of the cathode. The grid g_7 is a suppressor grid counteracting secondary emission of the anode; it is connected to the cathode.

The anode is connected to a high positive voltage (275 V) via a resistor of high value.

The grids g_1 and g_2 are so constructed that the field of g_3 and that of the electrodes beyond g_3 are ineffective at the cathode. Just as is the case with a pentode for instance, the electron current emerging through the openings of g_2 is thus only dependent upon the voltage of g_1 and that of g_2. Since these voltages are constant (0 and 20 V respectively) the electron current referred to is likewise constant.

The voltage at the control grid g_3, however, does indeed influence what further happens to this current: if the voltage of g_3 is negative the electrons return to g_2 (g_2 then takes up practically the whole of the cathode current); if g_3 is positive the electrons continue on their path and pass through the openings of g_4. What then happens to them is determined by the voltage at g_5: if g_5 is negative the electrons have to return to g_4; if g_5 is positive they continue on their way, passing through the meshes of g_5, g_6 and g_7 and reaching the anode, which is at a high positive potential.

Briefly it therefore amounts to this, that anode current can only flow when g_3 and g_5 are positive simultaneously and that this anode current (I_a) is constant (about 1 mA). (The currents taken up by the grids through which the anode current is flowing are small compared with I_a.)

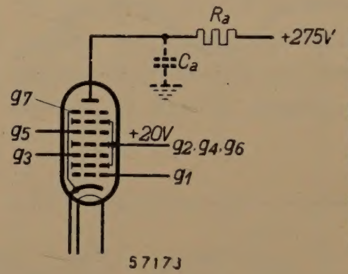

Fig. 6. Diagrammatic representation of the "φ-detector". g_1 = grid at approximately zero potential; g_2, g_4 and g_6 = screen grids at +20 V, g_3 and g_5 = control grids; g_7 = suppressor grid. R_a = anode resistance. C_a = anode stray capacitance.

If a sinusoidal alternating voltage is applied to each of the control grids and φ is the phase difference between these two voltages, then — according to the description given — anode current will only flow so long as both grids are positive. This is the case, in each cycle, during an interval of 180°—φ (*fig. 8*). Thus the anode current varies in block form between 0 and the constant value I_a. The mean value i_a of the anode current is therefore

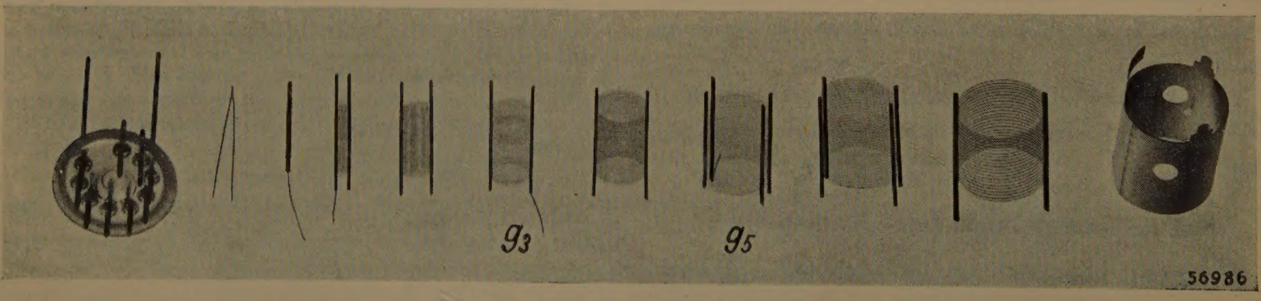

Fig. 7. Component parts of the "φ-detector". From left to right: the "Noval" base with 9 contacts pins, the filament, the cathode, the seven grids and the anode; g_3 and g_5 are the control grids. The illustration is about $^4/_5$ of the true size.

$$\bar{i}_a = \frac{180^\circ - \varphi}{360^\circ} \cdot I_a \quad . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

and is thus a measure of the phase difference φ. Hence the name of the valve: "φ-detector".

When the frequency-modulated i.f. voltage in an FM receiver is converted with the aid of a suitable network into two alternating voltages with a mutual phase difference φ varying proportionately to the frequency deviation, and these voltages are applied to the grids g_3 and g_5, then, according to (1), the mean anode current will vary proportionately to φ, thus likewise in proportion to the frequency deviation, or in other words proportional to the a.f. signal to be transmitted.

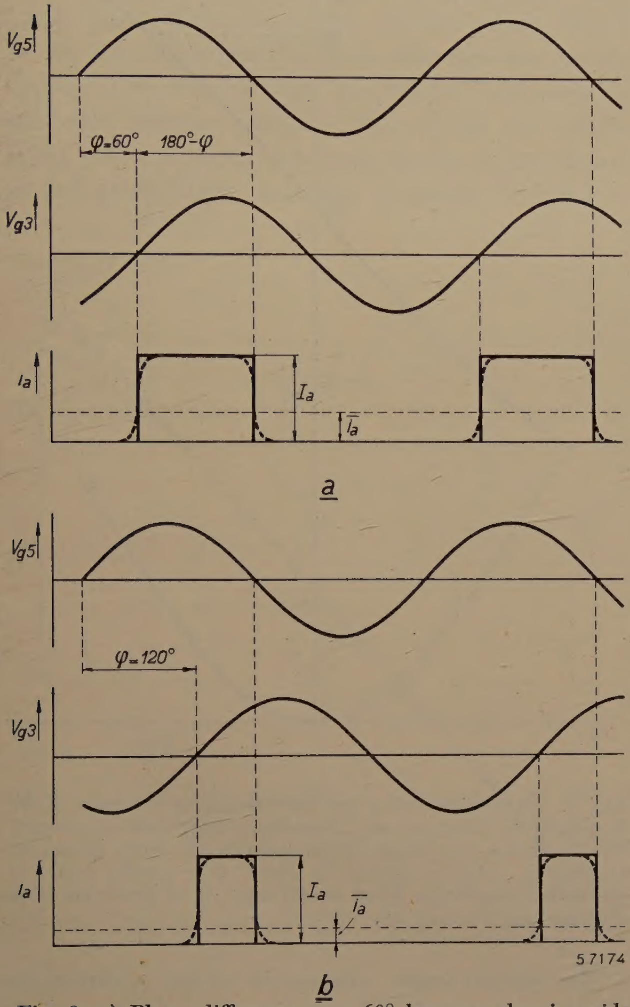

Fig. 8. *a*) Phase difference $\varphi = 60^\circ$ between the sinusoidal grid voltages v_{g3} and v_{g5}. Anode current i_a, with amplitude I_a and mean value $\bar{i}_a$.

b) The same for $\varphi = 120^\circ$; here $\bar{i}_a$ is half as great as in (*a*).

The rectangular pulses forming the anode current have the same periodicity as the intermediate frequency (about 10 Mc/s). The anode current therefore consists of an alternating current with this fundamental frequency (and its harmonics) superimposed on a direct current pulsating at the audio frequency. The anode resistor R_a (e.g. 0.5 MΩ) shunted by the stray capacitance of the anode C_a (about 25 pF) brings about an almost complete separation of these two components: the current changing according to the audio frequency flows through the resistor, whilst the i.f. current flows almost entirely through the capacitance. The internal resistance of the valve amounts to about 3 MΩ.

From (1) it is also to be seen that the "φ-detector" acts as a limiter: since, as we have seen, I_a is constant, also $\bar{i}_a$ is independent of the amplitude of the alternating voltages at g_3 and g_5.

For the sake of simplicity it has been assumed in the foregoing that the anode current changes discontinuously with the voltage applied to the control grids. Actually, however, a gradual transition takes place, about which more will be said farther on. As a result the rectangular shape of the anode current pulses is somewhat rounded off, as indicated in fig. 8. In essence the linear relation (1) between $\bar{i}_a$ and φ still holds.

Fig. 9 is an illustration of the "φ-detector" (type EQ 80). It is made in the same way as the "Rimlock" valves [4]) and, like these, has a diameter of 22 mm.

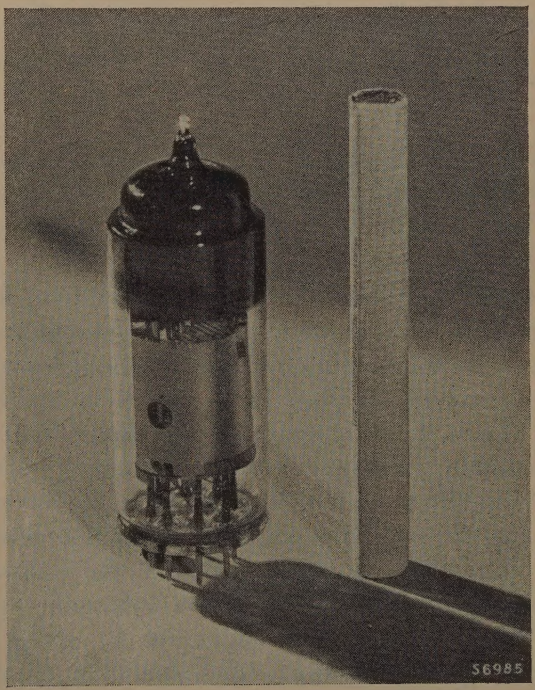

Fig. 9. The "φ-detector" EQ 80 with a cigarette for comparison of size.

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[4]) G. Alma and F. Prakke, A new series of small radio valves, Philips Techn. Rev. 8, 289-295, 1946. In contrast to the "Rimlock" valves, the EQ 80 has a "Noval" base with 9 contact pins placed at 9 corners of a regular decagon. The valve cannot be wrongly inserted in the holder because the latter has only 9 openings to match the pins. Since the EQ 80 requires only 8 leads, the cathode is connected to two contact pins.

Properties of the "φ-detector"

The "φ-detector" as frequency discriminator

Fig. 10 shows how the "φ-detector" can be used in a circuit. The i.f. transformer belonging to the i.f. amplifier, in which the first phase of the detection process takes place, namely the conversion of the frequency variations into φ-variations, consists for example of two coupled tuned circuits. Each of the circuits is connected to a control grid (g_3, g_5) of the "φ-detector". The amount of the phase difference φ between the voltages across the two circuits depends upon the instantaneous value f_i of the intermediate frequency. If the frequency deviation Δf_i is nil (as is the case if the transmitter is not modulated) then $\varphi = 90°$. When the transmitter is modulated f_i varies and φ shows a sweep around the value 90°. With the band-pass filter consisting of two tuned circuits as represented in fig. 10 the relation between φ and Δf_i is an arc cotan function (*fig. 11*) which in the vicinity of the point for $\Delta f_i = 0$ is only approximately linear. If at the maximum frequency sweep φ remains between 60° and 120° then the distortion due to the curvature of the arc cotan line amounts to 2.5% (curve D, fig. 11), which is to be regarded as the maximum permissible value. At the given frequency sweep, φ is kept between the said limits by giving the damping of the second band-pass filter circuit a suitable value. In this way reasonable linearity is obtained between Δf_i and φ.

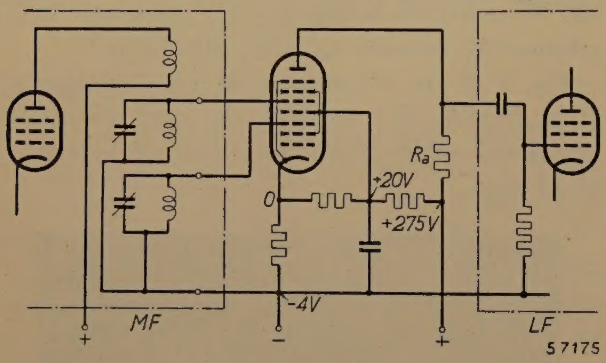

Fig. 10. Circuit for FM-detection with "φ-detector". MF = intermediate-frequency amplifier with a two-circuit band-pass filter, LF = audio-frequency amplifier.

It is to be noted that the distortion can be still further reduced at the extra cost of a more complicated filter. If a band-pass filter with three tuned circuits is used (*fig. 12*) under certain conditions the distortion is limited to 0.2% for φ = 60°-120° and to 1.2 % for φ = 50°-130°.

The conditions referred to are for example:

$$Q_3 = 0.45\ Q_2,$$
$$M_{23} = L_2/Q_2,$$

in which Q_2 is the quality factor of the circuit L_2-C_2 (fig. 12), Q_3 that of L_3-C_3 and M_{23} the mutual inductance between L_2 and L_3.

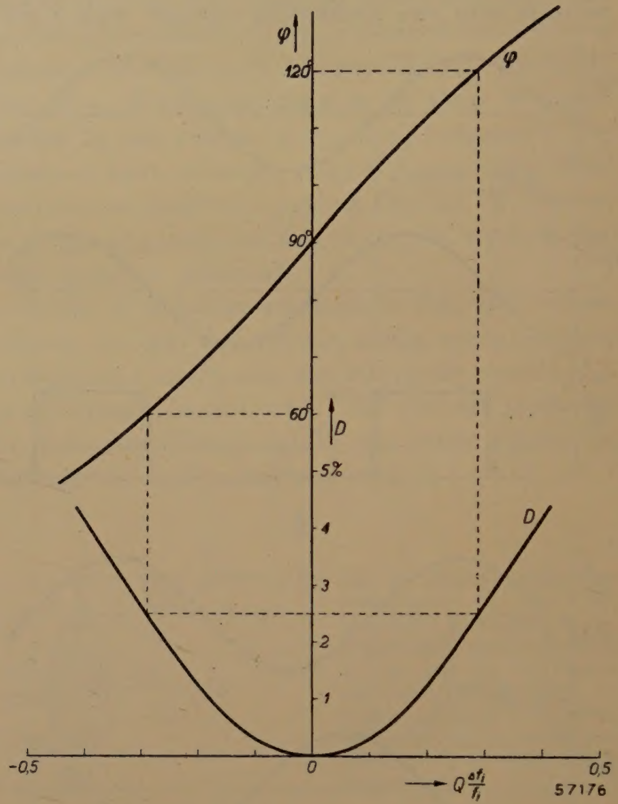

Fig. 11. Phase difference φ and distortion D as functions of the frequency deviation for an i.f. band-pass filter with two circuits. The distortion is a result of the φ-curve not being linear. As abscissa $Q \cdot \Delta f_i/f_i$ is plotted, in which Q = quality factor of the second band-pass filter circuit and Δf_i = deviation from intermediate frequency f_i.

The second stage, conversion of the φ-variations into proportional current variations, is the task of the "φ-detector". How this is achieved can be judged from the characteristics represented in *fig. 13*, where i_a is plotted as a function of φ for several

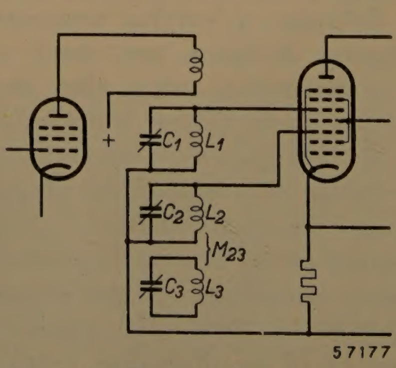

Fig. 12. Band-pass filter with three tuned circuits, by means of which the distortion can be kept smaller than with two circuits.

values of the alternating voltages $V_{g3} = V_{g5}$ at the control grids. It is seen that between $\varphi = 50°$ and 130° the relation between $\bar{i_a}$ and φ is practically linear. The slope in this range is 2.8 μA per degree phase difference. With a sweep of φ between 60° and 120° — limits within which φ is a practically linear function of Δf_i — the variation in the value of $\bar{i_a}$ thus amounts to $30 \times 2.8 = 84$ μA. The r.m.s. value of the a.c. anode current is then $84/\sqrt{2} = 60$ μA. This current flows through the anode resistor (0.5 MΩ) of the "φ-detector" shunted by the grid resistor (about 1 MΩ) of the a.f. amplifying valve, so that the voltage applied to the latter, at full modulation, amounts to about 20 V r.m.s.

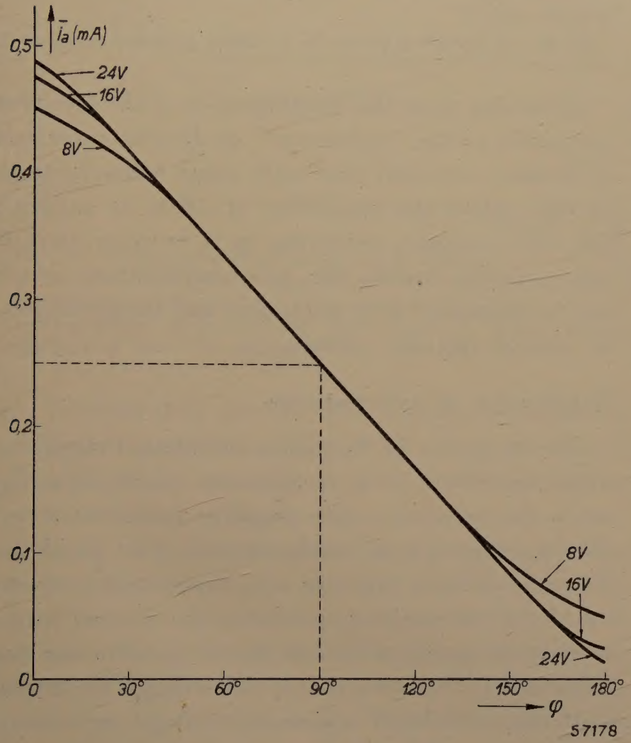

Fig. 13. Mean anode current $\bar{i_a}$ of a "φ-detector" as a function of the phase difference φ between the alternating voltages v_{g3} on the third grid and v_{g5} on the fifth grid, for $V_{g3} = V_{g5}$ respectively 8, 16 and 24 V r.m.s.

When a band-pass filter with three tuned circuits is used, the limits of the φ sweep can be chosen somewhat wider; the output voltage then rises to 25 V.

The "φ-detector" as limiter

Fig. 13 also shows that the "φ-detector", as already explained, acts as a limiter: within the above-mentioned limits of φ the curves $\bar{i_a} = f(\varphi)$ for various values of the alternating voltage $V_{g3} = V_{g5}$ at the control grids practically coincide, so that in the first instance amplitude modulation will not be detected. However, 8 V r.m.s. is the smallest value at which the curves sufficiently coincide and at which the linear part is sufficiently long. Therefore V_{g3} and V_{g5} must not drop below 8 V, a value which is rather higher than that required for some other FM-detectors but which will not as a rule be difficult to obtain.

In order to ascertain more accurately to what degree the "φ-detector" is insensitive to amplitude modulation, the following measurement has been taken. H.F. voltages not modulated in frequency but modulated in amplitude up to 30 % with a low frequency and having a constant phase difference of 90° were applied to the two control grids of the valve. The r.m.s. value I of the a.f. anode current was measured as a function of the amplitude of the control-grid voltage. If the "φ-detector" were absolutely insensitive to amplitude modulation — in other words, if the curves in fig. 13 were to coincide completely round about the point with abscissa $\varphi = 90°$ — then I would have to equal 0. The result of the measurement (*fig. 14*) shows that I is not quite zero but less than 1 μA, provided the control-grid voltages are greater than 8 V. (This value of I is to be compared with the value found above for the A.C. anode current at the full frequency sweep, viz. 60 μA.) The same applies for other values of φ between 50° and 130°. Thus all interference causing amplitude variations in the output voltage of the i.f. amplifier is effectively suppressed in the "φ-detector".

Contrary to the case with limiters having an *RC*-circuit (fig. 5), in the application of this detector as a limiter there is no other inertia than that of the electrons, so that the interferences are suppressed very quickly. Consequently, not only interference of a more or less continuous nature is suppressed

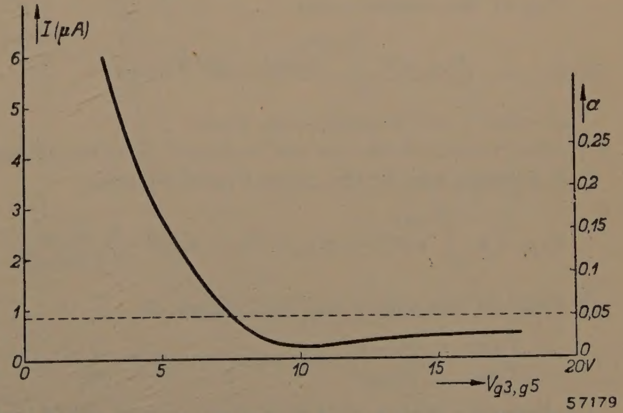

Fig. 14. R.m.s. value I of the a.f. anode current of the "φ-detector" as a function of the alternating voltage $V_{g3,g5}$ (r.m.s. value) at the control grids, in the case of 30% amplitude modulation and a constant phase difference $\varphi = 90°$ between V_{g3} and V_{g5}. When $V_{g3,g5} > 8$ V amplitude modulation is scarcely detected and the noise arising therefrom is less than that due to frequency modulation. (For the quantity α see the text in small type.)

(e.g. noise), but also short, impulse-like interference bursts such as may arise from transients due to transients in the mains or from the ignition in motor vehicles.

The extent to which a limiter should suppress amplitude modulation can be gathered from the following, taken partly from an article previously published in this journal[5]). Particular attention will now be paid to noise.

Suppose that at the output of an i.f. amplifier there is a signal with amplitude A, originating from the desired but non-modulated transmitter (interference is most troublesome during intervals in the modulation), and also a weak interfering signal with amplitude sA ($s \ll 1$), likewise non-modulated. Let the frequency difference between the two signals be f_a, a frequency in the audible range.

The combination of these two signals forms a signal the amplitude and frequency of which are both modulated, the amplitude with a modulation depth s, the frequency with the frequency sweep sf_a (see the first of the article quoted in footnote [5])). In both modulations the modulating frequency is f_a.

If this combined signal is applied to an amplitude detector then, roughly speaking, this yields an a.f. voltage with the amplitude sA and the audio-frequency f_a.

When, however, this combined signal, after all amplitude modulation has been removed in an ideal limiter, is applied to a frequency discriminator such as represented diagrammatically in fig. 2*a*, the discriminator yields a signal with the amplitude A modulated to a depth $sf_a/\Delta f_{max}$ (Δf_{max} is the maximum frequency sweep allowed by the discriminator). Upon this amplitude modulation being detected, the result is an a.f. signal again with the frequency f_a but with an amplitude sf_aA/f_{max}.

We shall now extend the single interfering signal from which we started to a noise, that is to say, to a continuous spectrum of interfering signals. We shall see what the result is a) after amplitude detection and b) after limitation and frequency detection.

a) After amplitude detection noise is produced, to the power of which, in any frequency interval df_a, the contribution is proportional to $s^2A^2df_a$. By integration over the range of the audio-frequencies ($f_a = 0$—$f_{a\,max}$) we find for the power P_{AM} of the audible noise:

$$P_{AM} = k \int_0^{f_{a\,max}} s^2A^2 df_a = ks^2A^2f_{a\,max},$$

in which k is a proportionality factor.

b) After complete limitation and frequency detection we find in a similar way for the power P_{FM} of the noise:

$$P_{FM} = k \int_0^{f_{a\,max}} s^2A^2f_a^2/(\Delta f_{max})^2\, df_a = ks^2A^2 \cdot \frac{1}{3} \frac{f_{a\,max}^3}{(\Delta f_{max})^2}.$$

Thus the two powers bear the relation of

$$\frac{P_{AM}}{P_{FM}} = 3\left(\frac{\Delta f_{max}}{f_{a\,max}}\right)^2, \text{ for which we write } = \frac{1}{a^2}.$$

A frequency detector without limiter would yield both the noise contributions (AM noise and FM noise) simultaneously. Of these two the AM noise is by far the stronger, as shown by the last formula given. If we substitute for Δf_{max} the usual value of 75 kc/s and for $f_{a\,max}$ 12 kc/s, we obtain:

$$P_{AM}/P_{FM} = 3 \cdot (75/12)^2 = 117.$$

We now have to consider how well a limiter must function in order to suppress the AM noise so far as to make it just as weak as the FM noise (further suppression would be of little avail). We see from the above calculation that the amplitude variations of the input voltage of the discriminator have to be attenuated to $1/\sqrt{117} \approx 1/11$ of the original value.

In this rough calculation no account has been taken of the fact that in an FM transmitter the high notes are given a certain pre-emphasis, that is to say they are transmitted with a strength proportionately too great, this being compensated in the receiver by a de-emphasis filter. Taking into account the influence of this filter, the value of the limiting factor a where the two noise contributions are equal is $1/20 = 0.05$ instead of 1/11.

In fig. 14 a scale is given for a, which is proportional to I.

Following upon this consideration of the foremost properties of the "φ-detector" as discriminator and as limiter, we shall deal with some other features of this valve: the possibility it offers to suppress the side response occurring in a receiver that is not properly tuned, the a.f. amplification which has to be applied after detection, and the possibility of simplifying the circuit.

Suppression of side response

The reception of frequency-modulated signals is often disturbed by a troublesome noise occurring when the receiver is not properly tuned, i.e. when the superheterodyne oscillator does not yield the frequency which, together with the central frequency of the transmitter, produces the central intermediate frequency to which the i.f. transformer has been tuned. The fact is that if the oscillator is so tuned that the modulated intermediate frequency sweep is in the area *II* or *III* (*fig. 15*) instead of in the

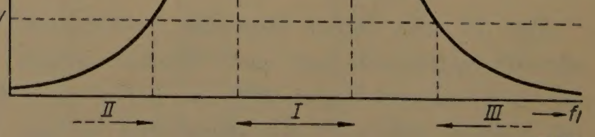

Fig. 15. Resonance curve of an i.f. transformer. With proper tuning the sweep of the intermediate frequency f_i lies in the area *I* and the output voltage $V_{g3,g5}$ is greater than the limit value of 8 V. In the case of incorrect tuning (area *II* or *III*) $V_{g3,g5}$ is too small

area I, the working point will lie in a part of the filter characteristic where strong amplitude modulation takes place, whilst the signal voltage remains below the limit at which the limiter comes into action. Thus the reproduction is distorted and accompanied by strong side response (interchannel noise) making it difficult to get the right tuning.

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[5]) Th. J. Weijers, Comparison of frequency modulation and amplitude modulation, Philips Techn. Rev. **8**, 89-96, 1946. For more detailed particulars see F. L. H. M. Stumpers, Theory of frequency-modulation noise, Proc. Inst. Rad. Engrs. **36**, 1081-1092, 1948 (No. 9).

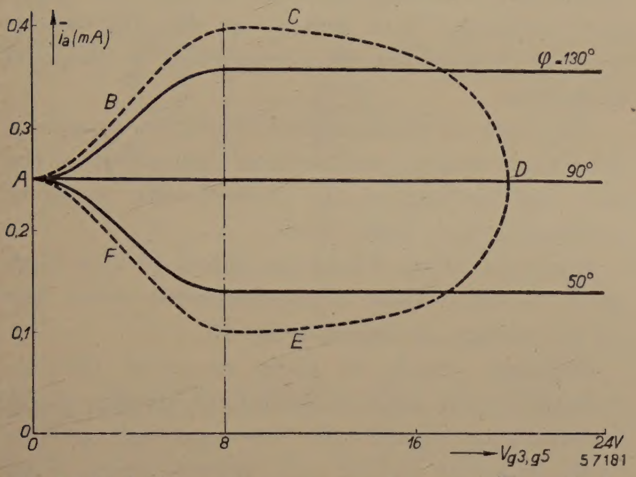

Fig. 16. Fully-drawn lines: mean anode current $\overline{i_a}$ of a "φ-detector" as a function of $V_{g3,g5}$ for several values of φ. Point A corresponds to a receiver very much out of tune, point D corresponding to a correctly tuned receiver. When turning the tuning knob the dashed line is followed.

We shall show how this side response is restricted as far as possible by means of the "φ-detector". It will also be seen that it can even be completely suppressed in a simple way.

In fig. 13 $\overline{i_a}$ is represented as a function of φ for some values of $V_{g3} = V_{g5}$. In order to see what happens when the receiver is detuned we prefer to choose the coordinates differently, plotting $\overline{i_a}$ against $V_{g3,g5}$ with φ as parameter. This gives curves as represented in *fig. 16* (continuous lines), from which it is also to be seen that if detection of amplitude modulation is to be avoided V_{g3} and V_{g5} must exceed a certain limit (8 V). If V_{g3} and V_{g5} are less than 8 V then $\overline{i_a}$ is dependent upon their magnitude, that is to say, the valve no longer functions as limiter.

The dashed line in fig. 16 denotes how $V_{g3,g5}$ and $\overline{i_a}$ vary when the frequency f_0 of the superheterodyne oscillator is gradually changed and the transmitter is not modulated. If there is still a great difference between f_0 and the transmitter frequency f_t then V_{g3} and V_{g5} are very nearly zero and in fig. 16 the position is thus represented at the point A. When f_0 is shifted towards f_t, so that $|f_t - f_0|$ approaches the frequency band passed by the i.f. circuits, V_{g3} and V_{g5} increase and the point indicating corresponding values of $\overline{i_a}$ and these voltages moves from A to B or F (according to the sign of $f_t - f_0$); let us suppose that it moves to the point B. Upon f_0 being further changed it passes through C to the point D, where correct tuning ($\varphi = 90°$) is reached. If f_0 were to be still further changed in the same direction the point would pass through E to F and finally, far beyond the tuning, reach A.

In the areas B and F, $\overline{i_a}$ depends upon the magnitude of V_{g3} and V_{g5}, so that the amplitude modulation of the signal is detected and the reproduction is distorted. The smaller the slope at B and F, the less this effect will however be. The shape of the curves given in fig. 16 is in fact much more favourable than that represented in *fig. 17*, where the slope is particularly steep at F. Such a state of affairs arises with a badly designed or improperly adjusted "φ-detector". The explanation of this is as follows.

So far we have been assuming for the sake of simplicity that the "φ-detector" is fully "open" at any positive value of the voltage at g_3 and g_5 and fully cut off at any negative value; in other words, that the characteristics $I_a = f(E_3)$ (with positive grid g_5) and $I_a = f(E_5)$ (with positive grid g_3) measured with a direct voltage (E) show the abrupt change represented in *fig. 18a*. Actually, however, these characteristics have a smooth slope (fig. 18*b* or *c*). If the characteristics are symmetrical with respect to a point P (fig. 18*b*) and this point

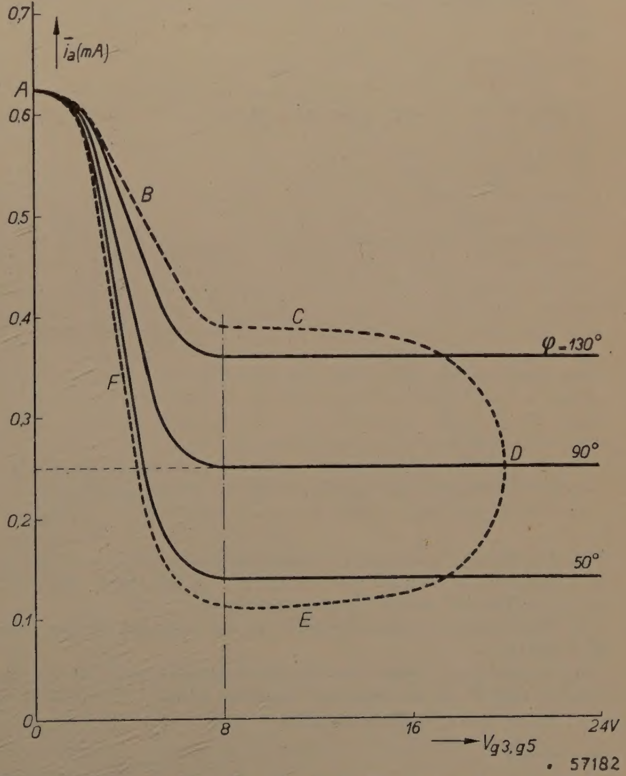

Fig. 17. As in fig. 16, but for a badly designed or wrongly adjusted "φ-detector". This functions properly at the correct tuning (D) but outside that point in the areas F and B of the dashed line, where $V_{g3,g5} < 8$ V, the sharp slope results in a greatly distorted reception and strong noise.

is, with the aid of a bias, chosen as working point, then the mean value of the anode current remains unchanged when an alternating voltage is applied to one of the control grids; the characteristics $\bar{i_a} = f(V_{g3,g5})$ and $\varphi =$ constant then have the symmetrical shape of fig. 16. If, however, the bias is improperly adjusted (working point for instance P' fig. 18*b*) or if one bend of the static characteristic is much less pronounced than the other (fig. 18*c*), a rather small alternating voltage applied to one of the control grids will give rise to a rectifying effect, with the result that $\bar{i_a} = f(V_{g3,g5})$ becomes asymmetrical in shape, the point A being situated either too high (fig. 17) or too low.

In the designing of the "φ-detector" particular care has been taken to ensure that the static characteristics are made symmetrical. By means of grids consisting of a helix with constant pitch, characteristics are obtained of the type indicated in fig. 18*c*, with a gentle upper bend and a sharp lower bend [6]). A known means of making the lower bend less sharp consists in giving the control grid a variable pitch; there are then, so to speak, a series of valves with mutually different characteristics connected in parallel. This means is commonly applied in variable-μ amplifying valves where the amplification is required to be gradually variable by changing the negative grid bias. This construction has been successfully applied also in the "φ-detector"[7]) in such a way that the characteristics obtained become symmetrical, as indicated in fig. 18*b*.

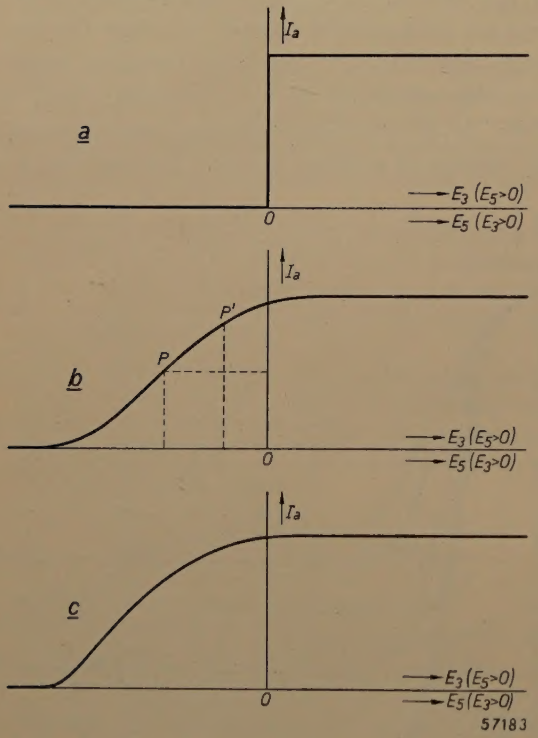

Fig. 18. Static "φ-detector" characteristics; anode current I_a as a function of the direct voltage E_3 on the third grid or E_5 on the fifth grid when E_5 respectively $E_3 > 0$.
a) Discontinuous characteristic, so far assumed for the sake of simplicity.
b) Continuous, symmetrical characteristic with P as the correct and P' as an incorrect working point.
c) Asymmetrical characteristic.

The slope of these characteristics has purposely been made rather small, so that inconstancy of the bias and shifting of the characteristic (contact potential!) have little effect.

The bias, which should be about —4 V on both grids, is taken from a potentiometer across the supply voltage, as shown in fig. 10.

Although, thanks to these measures, the "φ-detector" with such a circuit is already fairly favourable as regards the side response, one can easily go a step further and suppress interchannel noise entirely. This may be done by applying to g_1 an auxiliary voltage which cuts off the "φ-detector" cathode current so long as the voltage at the control grids g_3 and g_5 is less than 8 V. *Fig. 19* shows how this can be brought about: applied to g_1 are two direct voltages in series, a fixed negative voltage E_1 (taken from the potentiometer R_1-R_2-R_3) and a variable positive voltage E_1' (obtained from a diode rectifying one of the secondary voltages of the band-pass filter, and a smoothing capacitor). The "φ-detector" cannot come into action until the rectified voltage is high enough. A resistor R_4 prevents g_1 from becoming too strongly positive.

The diode can serve at the same time, in the known way, for automatic volume control and for controlling a tuning indicator.

Audio-frequency amplification

With the circuit shown in fig. 5 the maximum output voltage of the detector will scarcely reach 4 V. The "φ-detector", on the other hand, can give about 20 to 25 V, as already stated. This gain in output can be utilized in various ways.

With voltages of such amplitude it is possible, for instance, to control directly the output valve EL 41 [8]), which is already fully loaded with a control-grid voltage of 4 V; this leaves a factor of about 5 for the application of negative feedback, to counteract distortion by the output valve. This saves a stage of a.f. amplification.

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[6]) See J. L. H. Jonker, The control of the current distribution in electron tubes, Philips Res. Rep. 1, 331-338, 1946, in particular figs 4 and 5, or, by the same author, Current distribution in amplifying valves (Dutch), thesis Delft 1942, figs 68 and 69.

[7]) The irregular pitch of g_3 can be seen in fig. 7. This detail of g_5 has been lost in the reproduction.

[8]) Output pentode of the "Rimlock" construction (see footnote [4])) with a mutual conductance of 10 mA/V and an anode dissipation of 9 W.

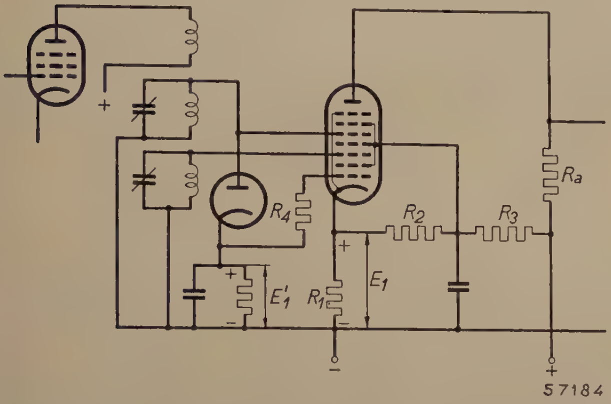

Fig. 19. The voltage at the first grid of the "φ-detector" amounts to E_1'—E_1, whereby E_1' is obtained by rectification of the voltage V_{g5} across one of the band-pass filter circuits. E_1 is so chosen that the "φ-detector" is cut off when $V_{g5} < 8$ V.

Mostly, however, it is required that the output valve of a receiver can be fully loaded already at the average modulation depth of the transmitter, which is about 25 %. If, whilst the output valve is just fully loaded, the modulation goes deeper or the volume control is turned higher, then some distortion arises, but the impression that the sound makes is determined more by the high notes it contains than by this distortion. In the case of an A. M. receiver with a relatively narrow frequency band, when there is a moderate overloading, the sound is not so disturbing, but it is so in an F. M. receiver, which reproduces also the highest audio frequencies; at these frequencies there is only a small margin between the audible limit and the bearable limit of the sound, so that when the sound is too strong the reproduction becomes disagreeable. This is all the more reason why no A.F. stage should be used between the "φ-detector" and the output valve. If ,however, it should nevertheless be desired to keep this stage then advantage can be taken of the high output voltage of the "φ-detector" by applying an exceptionally heavy negative feedback (thus making the distortion exceptionally small).

Simplicity of the circuit

When the circuit according to fig. 10 is compared with that according to fig. 5 it is seen that the "φ-detector" takes the place of the following components (without counting the less important ones): a pentode, a double diode and an i.f. transformer with two tuned circuits. One will particularly be glad to dispense with the i.f. transformer, which has to be so very carefully adjusted. There may be added the stage of a.f. amplification saved.

The circuit shown in fig. 19, where the "φ-detector" is blocked when the receiver is detuned, does not really entail any complication, because the diode, which as a rule is already present for tuning indication and automatic volume control, can be utilized for the object in view.

This ends the discussion of the properties of the "φ-detector". It has not been possible within the scope of this article to deal with a number of details, among others selectivity, which is particularly favourable when the "φ-detector" is used.

Summary. The "φ-detector" is a new valve for detecting frequency modulation. Of the seven grids which it contains, the second, fourth and sixth grids are screen-grids and the seventh is a suppressor grid. To each of the control grids (the third and fifth (an output voltage is applied from an i.f. transformer. The r.m.s. value of these voltages must be at least 8 V. The mean value of the anode current is a function of the phase-shift φ between the two control voltages, which phase-shift is in turn a function of the frequency deviation. Both functions are approximately linear when φ has a sweep between 60° and 120°. The amplitude of the anode current is not dependent upon the magnitude of the control voltages (provided they are greater than 8 V), so that the valve also acts as limiter. This renders certain sources of noise and of distortion harmless. Limitation takes place without any other inertia than that of the electrons, so that also short impulse-like interference bursts are limited. The "φ-detector" yields an a.f. voltage of about 20 to 25 V, so that an output valve can be fully loaded. With a "φ-detector" some of the components can be dispensed with, such as an i.f. transformer and two or three valves. The first grid can serve for blocking the cathode current in the event that the control voltages are not large enough, in this way suppressing the interchannel noise. The "φ-detector" EQ 80 is made in the same way as the "Rimlock" valves but has a "Noval" base (9 contact pins). The anode current (mean value) is only 0.25 mA.

AN APPARATUS FOR DETECTING SUPERFICIAL CRACKS IN WIRES

by P. ZIJLSTRA.

620.191.3:621.317.39:621.317.336

High-frequency alternating currents are not only used in radio and telecommunication engineering but can often also be employed for testing purposes, their high-frequency character being an advantage for some purposes. An example of such an application is the testing of wires for superficial cracks. The currents induced in a wire, when this is placed in a high-frequency magnetic field, flow almost exclusively along the surface, so that a superficial crack will greatly influence these currents and thus can easily be detected by a suitably chosen electrical measurement.

Introduction

For connecting the electrodes of electronic valves to other circuit elements use is made of wire or rod-shaped leads (e.g. lead pins). These have to be fused into the glass base of the valve in such a way as to ensure a vacuum-tight seal.

For good vacuum-tight sealing it is serious if there are fine cracks on the surface of the lead (as may easily be the case particulary with fairly thick wires) because in the fusing process the crack is not entirely filled with the glass and air can therefore leak in. This is particularly the case if the crack runs in the longitudinal direction of the wire or rod. In order to detect the presence of such cracks before a valve is mounted it is very convenient to have an apparatus with which the leads can be quickly tested.

The use of such an apparatus need not be confined to the testing of leads. For instance it is also highly important that in the manufacture of large electronic valves the thick filaments should be previously tested for the presence of fine cracks, since these are apt to lead to premature rupture of the wire.

In this paper an apparatus is described which has proved quite satisfactory for this purpose in practice. First we shall explain the principle of the method applied.

Principle of the method of testing

When a conducting wire or rod is placed in a coil through which a high-frequency alternating current is flowing, Foucault currents are induced in that wire or rod and at high frequencies these currents flow almost exclusively along the surface of the wire (the so-called skin effect).

Let us imagine that a round metal rod is placed inside a cylindrical coil with its axis coinciding with that of the cylinder. The combination of coil and rod may be regarded as a transformer with its secondary winding consisting of one single short-circuited turn, viz. the cylindrical surface layer of the rod through which the Foucault currents flow. The impedance of this transformer, considered from the primary side, depends, inter alia, upon the resistance and self-inductance of the secondary winding and the coupling between the primary and secondary windings. This means that this impedance is related to the shape of the cross section of the rod.

If there is a crack in the surface of the rod then the impedance will differ from that obtained with a sound rod, particularly if the crack is not a gentle hollowing out but a sharp cleft in the practically circular profile of the cross section. It will be readily understood that the presence of such a crack increases the length of the path travelled by the induced high-frequency currents, this resulting in an increased resistance of the "secondary winding" of the transformer. This change in resistance is manifested on the primary side of the transformer by a change in the impedance of the coil. (To a first approximation the self-inductance will not change.) All that is now necessary is to connect the coil to a circuit with which any change in the impedance can easily be measured.

When a rod that has to be tested is drawn through the coil any change observed in the impedance gives an indication of the presence of a crack.

It is of importance to investigate what magnitude the change in impedance can be expected to assume. To that end we have to calculate the reaction of the rod upon the coil and see how a fine crack in the rod passed through the coil influences this effect. Assuming, for instance, that a molybdenum wire 1.5 mm in diameter and having a longitudinal crack 0.1 mm in depth is passed through the coil, then it will be found that (at the frequency used in the apparatus) the coil resistance increases by 1/3%. Even such a small variation can be observed quite well by the method applied by us.

Reaction of the rod upon the coil

We will consider a cylindrical coil with an average radius of r_1 metres [1]) and of a length that is great compared to its diameter. Placed concentrically inside the coil is a cylindrical rod with a radius of a metres. Let us suppose that the rod consists of a material having a specific resistance ϱ (ohm.metre) and a relative permeability μ_r, and that an H.F. current $I_1 = I_{1\max} \sin 2\pi ft$ is flowing through the coil.

The magnetic alternating field H in the space between the coil and the rod has everywhere the same value H_1, which is given by the formula

$$H_1 = nI_1 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

in which n is the number of turns per metre of the coil.

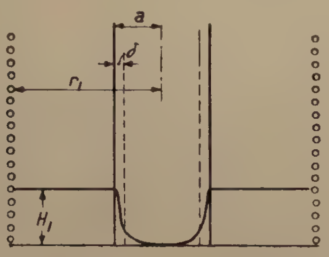

Fig. 1. Diagrammatic representation of the variation of the magnetic alternating field H inside the measuring coil (radius r_1) and in the rod (radius a). δ represents the penetration depth.

In the rod alternating currents are induced which, given a sufficiently high value of the frequency f, flow mainly along the surface of the rod. The current density is maximum at the surface of the rod; it decreases rapidly in the axial direction (whereby also the phase of the current changes continuously) and at a depth δ (the so-called penetration depth) it drops to $1/e$ times its greatest value (e = base of the natural logarithmic system). As the calculation shows, also the magnetic field rapidly decreases inside the rod: at the surface $H = H_1$ and at the depth δ H_1 has dropped to H_1/e (see *fig. 1*). The relation between the quantities δ, f, ϱ, and μ_r is given by the equation

$$\delta = \sqrt{\frac{\varrho}{\pi f \mu_0 \mu_r}} \text{ metres,} \quad . \; . \; . \; . \; . \; . \quad (2)$$

in which μ_0 = the vacuum permeability $= 4\pi \cdot 10^{-7}$ H/m.

The penetration depth δ is at the same time the thickness of an imaginary current envelope which, in the case of homogeneous distribution of the total current over this envelope, gives the same quantity of heat as the actual current. The Joule heat developed in the rod per metre length is given by the formula

$$P = H_{1\max}^2 \, \pi a \varrho / \delta \text{ watts,} \quad . \; . \; . \; . \; . \; . \quad (3)$$

which with the aid of (1) can also be written as

$$P = I_{1\max}^2 \, \pi \, n^2 a \varrho / \delta = I_{1\mathrm{eff}}^2 \, 2\pi \, n^2 \, a \varrho / \delta \quad . \; . \; . \quad (4)$$

Formula (4) shows that the heat development in the rod per metre length corresponds to that of a resistor connected in series with the coil:

$$R' = 2\pi \, n^2 a \, \varrho / \delta \text{ ohm} \quad . \; . \; . \; . \; . \; . \; . \quad (5)$$

Thus this gives the reaction of the rod upon the impedance of the coil in so far as the resistance component is concerned.

The self-inductance of the coil is also changed by passing the rod through the coil. Before the rod was introduced the self-inductance per metre length of the coil was

$$L = \pi \mu_0 r_1^2 n^2 \text{ henry} \quad . \; . \; . \; . \; . \; . \; . \quad (6)$$

After the rod has been inserted in the coil the magnetic field, roughly speaking, continues to exist only in the space between the coil and the rod, the cross-sectional area of which equals $\pi\,(r_1^2 - a^2)$. Originally there was the same magnetic field in the whole of the space enclosed by the coil (cross-sectional area $= \pi r_1^2$). Thus the reduction of the self-inductance of the coil due to the presence of the rod amounts per metre length to

$$L' = \pi \, \mu_0 \, a^2 n^2 \text{ henry} \quad . \; . \; . \; . \; . \; . \; . \quad (7)$$

As an example we will consider the case of a coil having an average radius $r_1 = 2.83$ mm and with a number of turns per metre $n = 26{,}000$, this coil being fed with a high-frequency current of the frequency $f = 5.6 \times 10^6$ c/s. The quality factor $Q = 2\pi fL/R$ of such a coil (without the rod) proved to be 17.6.

From these data it follows that the high-frequency resistance R and the self-inductance L of the coil (without rod) per metre length amount respectively to:

$$R = 42{,}700 \text{ ohms,} \qquad L = 0.0214 \text{ henry.}$$

A molybdenum wire 1.5 mm in diameter is now inserted in this coil. The specific resistance of molybdenum is $\varrho = 5.7 \times 10^{-8}$ ohm·metre, whilst $\mu_r = 1$. A calculation of the penetration depth with the aid of formula (2) gives $\delta = 50.8 \times 10^{-6}$ metres (thus about 50 microns). The increase in resistance of the coil due to the presence of this molybdenum wire is found directly from formula (5). Per metre length $R' = 3576$ ohms. Comparing this value with that of R it appears that the coil resistance has increased by a good 8%. Further, from (6) and (7) it is found that the self-inductance is reduced by about 7% of the original value.

What, now, is the effect of a crack in the surface of the rod upon the change in impedance of the coil? We shall investigate only the influence this has upon the resistance variation because it is mainly this that plays a part in the measurements taken with the apparatus which will be described farther on.

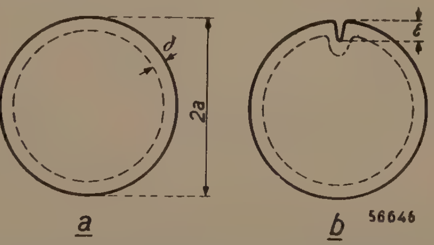

Fig. 2. Cross section of a rod where δ is the penetration depth of the induced Foucault currents. a) A sound rod or wire. b) A rod having a crack in the longitudinal direction to a depth ε.

As we have seen, the current in the wire is practically confined to a thin surface layer of the thickness δ (*fig. 2a*). The resistance of this thin layer (per metre length of the wire) is $2\pi a \varrho/\delta$ ohm, which expression is found in formula (5). If one narrow crack (of the depth ε) is present we may assume, as an approximation, that the flow of current will pass round the crack, so that its resistance will amount to $(2\pi a + 2\varepsilon)\,\varrho \cdot \delta^{-1}$ ohm. It may therefore be expected that owing to the crack the resistance R' will increase in the proportion of $(\pi a + \varepsilon)/\pi a$.

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[1]) In the calculations we shall use the Giorgi system of units.

Let us now take again a molybdenum wire with a radius of 0.75 mm as an example and imagine that it has a crack 0.1 mm in depth running along its entire length. The resistance R' will then increase to the extent of 152 ohms, i.e. by about 4%. Thus the total coil resistance formed by R and R' in series (42,700 ohms + 3576 ohms) increases by $^1/_3$%.

Further details of the method

It is now only a question of designing a circuit by means of which changes in the impedance of the coil of the given order of size can be measured with sufficient accuracy. For this purpose one can use, inter alia, a high-frequency bridge circuit or an oscillator circuit. We have chosen the latter and introduced the coil in the grid circuit of the oscillator, with a grid capacitor and leak resistor connected in the usual manner. Contrary to the methods already known, instead of the frequency change of the oscillator being taken as a measure for the change in the impedance of the coil, the influence of the impedance variation upon the control-grid current was taken as the measure. The principle of the circuit used is illustrated in *fig. 3*.

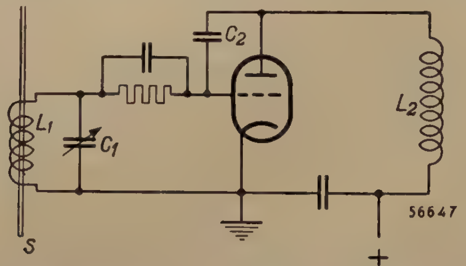

Fig. 3. Basic diagram of the apparatus for testing wires. The rod or wire S to be tested is passed through the coil L_1 which, together with a variable capacitor C_1, is included in the grid circuit of a radio valve. L_2 is the coil in the anode circuit and C_2 a feedback capacitor.

The grid circuit is formed by the coil L_1 (inside of which is the rod to be tested) and a capacitor C_1. The anode circuit comprises only a coil L_2, whilst the feedback via the grid-anode capacitance of the valve is augmented by an extra feedback capacitor C_2.

With such a circuit the magnitude of the control-grid current is to a first approximation proportional to the impedance $L_1/(R+R')C_1$ of the circuit. If $R+R'$ increases by $^1/_3$% then, as calculated above for a specific case, this results in a decrease of $^1/_3$% in the impedance and also in a reduction of $^1/_3$% in the grid current of the oscillator valve.

With the apparatus described in this article the grid current amounts to 2 mA. Thus, a crack in the rod resulting in a change of $^1/_3$% in the resistance causes the current to decrease by about 7 μA.

In order to observe such small current variations with sufficient accuracy a compensating circuit was used which reduces the current flowing through the measuring instrument from 2 mA to 100 μA.

With the aid of this compensating circuit the presence of cracks of the order of 0.1 mm depth can easily be detected. Where there are deeper cracks one will of course find a greater difference in the current intensity.

Description of the apparatus

The circuit diagram of the instrument is given in *fig. 4*, where L_1 is the measuring coil and C_6 the tuning capacitor of the grid circuit; R_4 and C_1 are respectively the grid leak and the grid capacitor, while C_2 and C_3 together form the feed-back capacitor. The coil L_2 is the anode choke. The anode and the grid d.c. circuits are decoupled by means of the by-pass capacitors C_4 and C_5.

The variations in current are read from the micro-ammeter, care being taken that the circuit oscillates adequately by adjusting the capacitors C_6 and C_3. The oscillator valve B_1 is a triode, the grid current of which is adjusted to about 2 mA. The compensation circuit already mentioned ensures that only a small part of this grid current (100 μA) passes through the micro-ammeter. The grid current flows from the grid via the cathode, micro-ammeter, selenium rectifier Se_1, through L_1 and R_4 back to the grid. If Se_1 were taken away the compensating current would flow from the positive side through R_1, R_2 and R_3 and back in the opposite direction through the micro-ammeter to the negative side. The difference of these two currents results in a current in the pass direction of the selenium rectifier.

The resistor R_3 is variable so that the compensating current can be adjusted to allow current readings to be taken from the micro-ammeter with rods of different diameters.

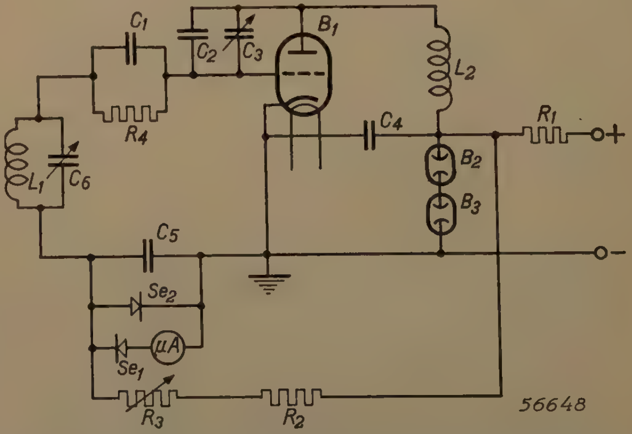

Fig. 4. Circuit diagram of the apparatus for testing wires. B_1 is the valve with the measuring coil L_1 in its grid circuit; B_2, B_3 are stabilizing valves, L_2 is the anode coil, Se_1 and Se_2 are selenium rectifiers.

Since the grid current is dependent not only upon the impedance of the grid circuit but also upon the direct voltage of the anode, the rectifier for the anode supply is provided with a voltage stabilizer consisting of two stabilizing valves B_2 and B_3 with a resistor R_1.

The valve acting as rectifier in the high-tension unit needs a longer time to warm up than B_1. This is of importance because it avoids the compensating circuit coming into action before the oscillator starts supplying current; if that were to be the case then the micro-ammeter might easily be overloaded when switching on.

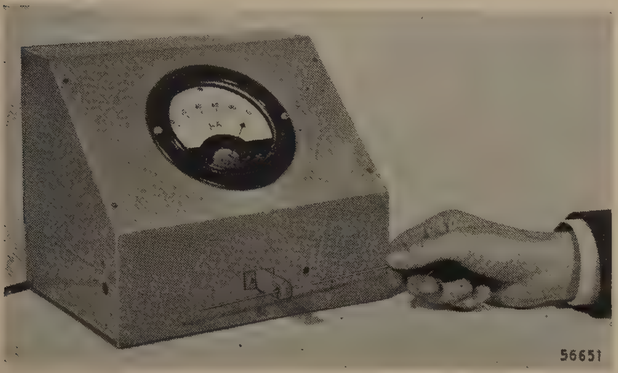

Fig. 5. Photograph of the apparatus described in this article being used for the testing of a wire.

The micro-ammeter is also safeguarded against overloading in another way. When the apparatus is switched off the grid current drops much quicker than the compensating current. The rectifying cell Se_1 then prevents the compensating current from flowing through the micro-ammeter, whilst the rectifying cell Se_2 forms an additional shunt for the leakage current from Se_1. *Fig. 5* shows the apparatus in operation.

Applications

As stated already in the introduction to this article, the apparatus described here has been designed for testing the lead pins of electronic valves. These are mostly made of molybdenum or tungsten in the form of rods with diameters of about 0.75 up to 2.5 mm. Not only these pins, already cut to size, but also the rods or wires from which they are made can be passed through the apparatus, thereby detecting any faulty parts and thus saving cutting and grinding costs. A larger measuring coil can be fitted in for testing thicker rods up to a diameter of 6 mm.

This apparatus has also been found very useful for the testing of tungsten filaments for large transmitting valves. It has been found that the cases of filament rupture that used to take place now and then were caused by long cracks in the wire. These wires are therefore now passed through the apparatus for testing before being cut to size.

Wires possessing ferromagnetic properties cannot be tested with this apparatus because local variations in permeability give rise to so many changes in the meter reading that those due to the presence of cracks cannot be distinguished.

Apart from its use for the detection of cracks, this apparatus is also suitable for detecting variations in the cross section of a rod or wire, provided this is accompanied by a variation in the length of the periphery. Thus it is possible to find local thickening or thinning in this manner; it is not necessary that the normal rod should have a circular profile.

Another application lies in the sorting of pins of equal dimensions but having divergent properties in their material. Pins not conforming to a specified composition can easily be picked out with this apparatus on account of the different value of their specific resistance.

Summary. For the proper functioning of electronic valves it is necessary that there should not be any fine cracks on the surface of the leads passing through the glass. In this article an apparatus is described with which the presence of such cracks can be detected. The rod or wire to be tested is placed in a measuring coil through which a high-frequency current is passed. If there is a crack in the wire then the impedance of the coil will vary from that obtained with a sound rod or wire. In order to determine this difference the coil is included in the grid circuit of an oscillator. The extent of the variation in impedance is derived from the influence that this has upon the control-grid current. The method is sufficiently accurate to detect cracks of about 0.1 mm depth. The use of this apparatus is not confined to the testing of valve leads; it can be used also in other cases for the testing of wires.

FLUORESCENT PIGMENTS AS AN ARTISTIC MEDIUM

by J. L. H. JONKER and S. GRADSTEIN

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Tradition has it that in China about the year 1000 A.D. there was a picture by a Japanese artist representing an ox which was invisible by day but could be seen in the dark on account of light being emitted from it. Painting with luminescent materials is therefore in fact fairly old. That picture, however, must have been painted only for the mysterious effect of the afterglow. In the experiment described in this article there was no such intention, the object being to make use of the vivid colours produced by fluorescent substances under ultra-violet radiation. Fluorescent pigments have a selective emission, whereas the pigments commonly used in art painting are characterized by a selective absorption and reflection. The consequences of this difference, both for the practical realization of the experiment in question and for the possible artistic value of the new technique of painting, are explained in this article.

The wide use being made nowadays of fluorescent substances for various industrial products (fluorescent lamps, cathode-ray tubes, etc.) has stimulated the development of a number of new substances of this kind. The beautiful colours and the high light yield of many of these new substances have in turn led to the search for further possible applications. One example that has aroused considerable public interest is the application of these substances for decorative purposes. Stage scenery, costumes, and all sorts of objects for attracting attention in exhibitions or in shop-windows are painted with fluorescent paints. When all visible light is excluded and the invisible ultra-violet radiation from a mercury lamp is projected onto the scenery or the object, astonishing effects are produced because the objects themselves are apparently emitting light in all sorts of vivid colours.

It is obviously only one step further to use fluorescent pigments for making a picture. By way of experiment one of the authors of this article (J. L. H. J.) ventured to take that step a few years ago (1946). *Fig. 1a* gives a coloured reproduction of the result, which was exhibited, inter alia, at a meeting of the "Commission Internationale de l'Eclairage" (International Commission of Illumination) held in Paris in June 1948. In what follows something will be said about the artistic aspects and the practical problems of this new technique in the art of painting.

The world that the artist aims at representing — presupposing that that is indeed his aim — is characterized from the physical point of view by the differences in colour and brightness of the objects perceived by the eye. In the classical techniques, such as painting in water-colours, pastel drawing, oil painting, the artist has a sufficient variety of paints on his palette to be able to represent faithfully the different colours occurring in nature. In trying to represent the brightness values occurring in a scene however he is at a disadvantage. Obviously one cannot expect a faithful imitation of the high brightness of all sorts of light sources; no one would blame the artist for a yellowish round spot on the canvas giving only a poor impression of the radiant sun it is supposed to represent. But even disregarding the high brightnesses of light sources, a faithful reproduction of the degree of brightness of most subjects remains an impossibility. It is

Table I. The measured brightness range (ratio of the greatest to the smallest local brightness) of different objects [1]).

Object	Lightest part	Darkest part	Brightness range
Open-air scene	White house in the sun	Black cat in the shade	90
Living-room	Light wall-paper in the sun	Black mantle-piece in shadow	5000
Living-room	Light wall-paper in diffuse daylight	Black mantle-piece in shadow	80
Cinema picture (for comparison)	—	—	25-80

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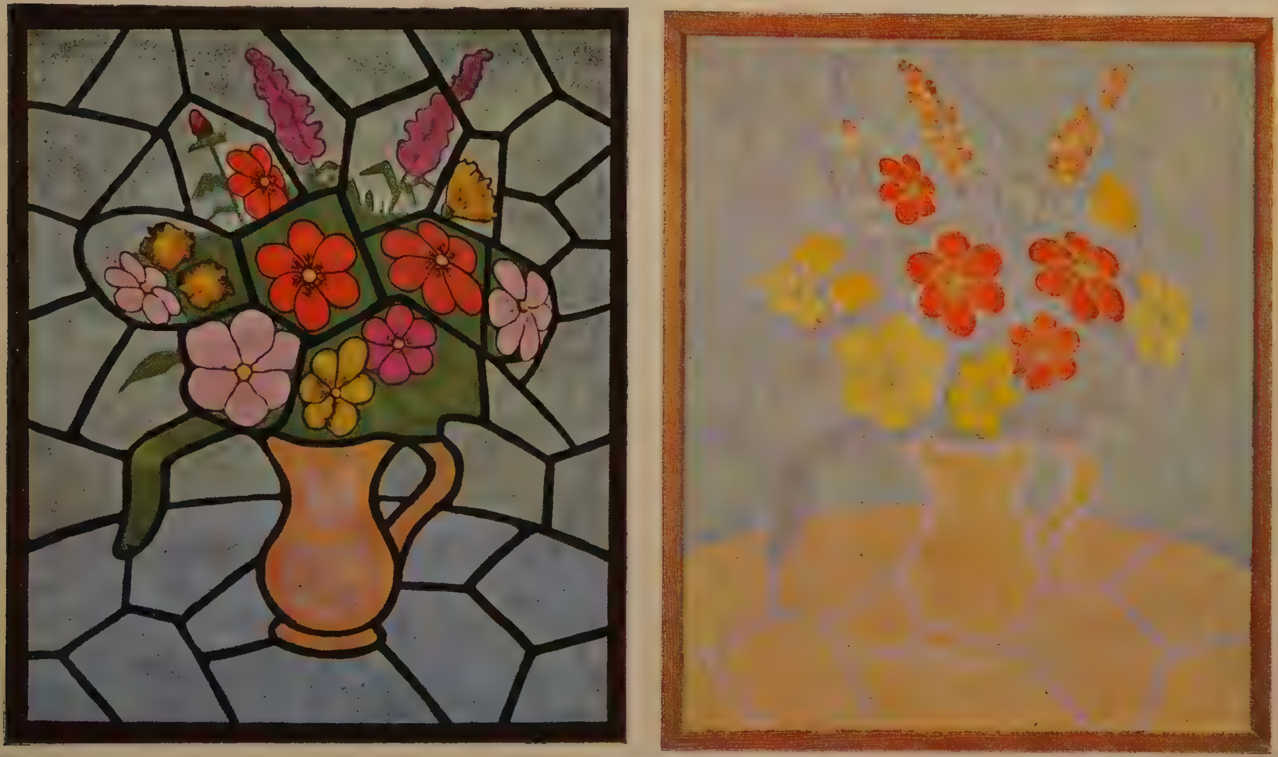
[1]) Taken from General Electric Review 48, September 1945, page 18. A more extensive treatise, with figures, on the brightness ranges occurring in nature is to be found in E. Goldberg's "Der Aufbau des photographischen Bildes, I. Helligheitsdetails", publ. Knapp, Halle 1925. And further see L. A. Jones and H. R. Candit: The brightness scale of exterior scenes and the computation of correct photographic exposure, J. Opt. Soc. Amer. 31, 651-678, 1941.

not unusual for the "brightness range", i.e. the ratio of the greatest and smallest brightnesses occurring, of an indoor subject to amount to a factor of 1000 or still more; in the open air, owing to the equalizing effect of the contribution of diffuse light from the vault of the heavens, the brightness range is generally smaller (see *table I*), but in the presence of glass or water, owing to reflections from their surfaces, the brightness range in the open air may also be far more than 1000. The greatest difference that the artist can produce between light and dark however is only a factor of 20 to 50, according to the technique chosen (see *table II*).

The artist is fully conscious of this shortcoming and tries to meet it in various ways. To lend more brightness to a patch of colour he chooses contrasting colours for the adjoining parts of the picture (blue shadows against yellow lights) or tempers their brightness. He enhances the effect of reflections by flattening with a palette knife the pure white that he uses for these effects, thereby avoiding cast shadows from the uneven surface; etc. If one speaks of the "simulation of light" by famous painters such as Leonardo da Vinci, Rembrandt or one of the great impressionists, it must be realized that each case is in fact a special example of the art of manipulating the limited scale of brightness in order to produce the greatest artistic effects.



a *b*

Fig. 1. Reproduction of the fluorescent painting
a) when exposed to ultra-violet radiation,
b) when exposed to daylight.
In the case *a*) two "Biosol" mercury lamps were used for irradiation. Filters of nickel-oxide glass absorbing practically all the visible rays were placed in front of the lamps. In front of the lens of the camera a filter was used which absorbs the ultra-violet rays. The latter was necessary because the painting reflects a large part of the incident ultra-violet light, to which the photographic plate is sensitive.

The specific impression that the fluorescent painting under ultra-violet irradiation makes upon the observer cannot, fundamentally, be fully represented by the reproduction; the reason for this is explained in the text.

Table II. The brightness range in various techniques of painting. The brightness was measured, relatively, of the clearest white and the darkest black of each technique (with the same intensity of illumination for all four techniques). Each colour was applied in a well-covering layer on an area of about 10 cm × 10 cm (4″ × 4″).

Technique	Base	Brightness of white	Brightness of black	Brightness range
Water-colour	white paper	4.58	0.211	22
Pastel	grey paper	4.35	0.112	39
Gouache	white paper	5.85	0.130	45
Oil painting	painters' canvas	4.45	0.096	46

There has been no lack of attempts to raise the brightness range of a painting. Perhaps one of the oldest known cases is that of the painter Mariotto Albertinelli, who worked at Florence about 1500. Vasari[2]) tells of the efforts of Albertinelli to produce a highly plastic effect by means of deep shadows while still bringing out details among the shadows. When this proved unsuccessful, even after transposing the piece to higher or lower brightnesses, it occurred to him that he would have to try to find a brighter white for the high lights, and so he attempted to increase the purity of the white-lead paint used at that time, though without success.

Some painters have tried to solve the problem by gluing small mirrors of glass or metal onto the canvas where the high lights occur and partly covering these with paint. It is obvious that the effect of this artifice depends very much upon the direction of the incident light and consequently cannot, in general, give satisfaction.

Rather than attempt to get a brighter white, it is better to try to increase the brightness range by making the black darker. On the white side, where the reflection is 80-90 %, at most a factor of 1.1-1.2 can indeed be gained. The shortcoming of the normal techniques of painting lies rather in the fact that the "black" is never quite so black, corresponding mostly to a reflection coefficient of 2-5 % (from which then follows the abovementioned limit of 50 for the brightness range). In principle, therefore, much more is to be gained on this side. Several methods of getting a deeper black are described in a patent granted to F. Blau[3]). These methods amount to this, that, at the places where no reflection towards the eye of the observer is desired, either the light is allowed to pass through the picture to be absorbed in a "black body" behind it, or the light is caused to be reflected in directions other than those of the observer by applying directed lighting and a reflecting background in the picture. A difficulty then, however, is to get intermediate tints; for this purpose a sort of pointillism technique has been proposed, among others.

It may be surprising that the problem of brightnesses should find a satisfactory solution, without any further artifices, in the application of fluorescent pigments. Putting it paradoxically, we might say that this is due to the non-fluorescing parts in and around the painting! If no other light whatever is allowed to fall on the painting and the visible light from the mercury lamp used for irradiation is filtered out, these non-fluorescent parts can be almost absolutely black. The brightness range of the fluorescent picture may then theoretically reach the value of infinity!

The brightness range measured on the fluorescent painting was about 130. The fact that the infinite value is not reached is due to two causes acting in conjunction. In the first place the filter used in front of the mercury lamp (a nickeloxide glass) allows a little red and violet light to pass through it, and furthermore the human eye is not quite insensitive to the ultra-violet mercury line with wavelength 3650 Å by which the fluorescence is excited. In the second place the backing of the picture (and the frame, etc.), though it does not fluoresce at all, will always reflect to a certain extent the ultra-violet and the violet and red, and will thus possess a definite though very small brightness. In our case the situation in this respect was as unfavourable as possible, because normal linen with a white chalk base was used as a backing for the picture. In the filtered mercury light the white chalk, owing to the reflection, is much less "black" than one would expect. Nevertheless, according to the values mentioned, a factor of 3 to 4 has already been gained in brightness range compared with the normal techniques of painting. An experiment with a backing that was black in the visible light (and also non-fluorescent) showed that a brightness range of more than 1400 could thereby easily be reached (the brightness of the "black" under ultra-violet irradiation fell below the sensitivity of the measuring apparatus employed).

In addition to the large brightness range of the fluorescent picture there is yet another point. In the normal techniques of painting there is no objection to translating "brightness range" by the more familiar "difference between the brightest white and the darkest black". When painting with fluorescent pigments, however, this translation would be incorrect, for here we have the remarkable fact that some colours are brighter than the brightest possible white! This fact, which from the artistic point of view may of course also be of great importance, can be explained as follows.

A normal pigment owes its colour to the absorption of a specific part of the spectrum of the light falling upon it. The more saturated a colour is, the narrower is the part of the spectrum that the pigment reflects (or allows to pass through). Consequently the total reflection coefficient of a pigment, and with that also its brightness under a given intensity of light, will necessarily decrease according as the colour is more saturated 4); see *fig. 2*. The brightest possible colour is that having a saturation zero, and that is white.

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[2]) G. Vasari, Le vite de' più eccellenti architetti, pittori e scultori, Florence, Torrentino 1550.

[3]) See Z. techn. Phys. **6**, 279-280, 1925 (Dr. Blau - Festschrift).

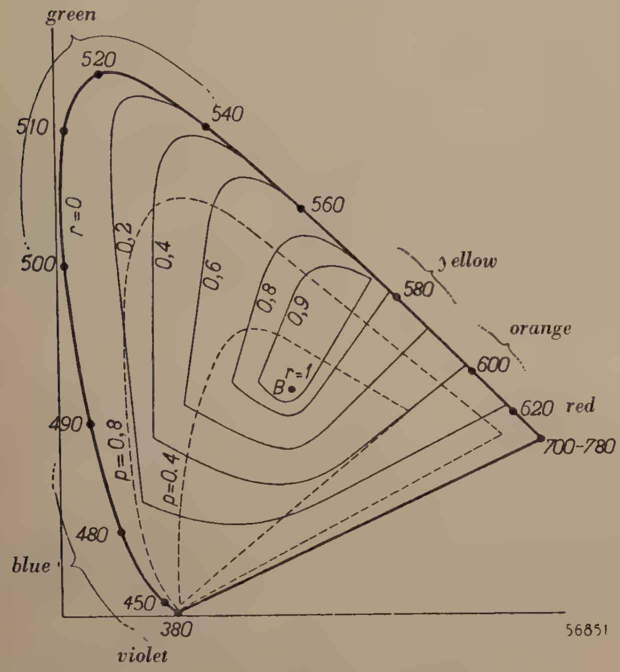

Fig. 2. In the chromaticity triangle, for each point characterized by the hue and the degree of saturation there is a maximum total reflection factor *r* that can be theoretically reached. (The pigment with that colour point must possess a spectral reflection curve of a certain shape to obtain the maximum reflection factor.) In the diagram, which applies for the case where the pigments are exposed to sunlight (so-called standard illuminant *B*), each fully-drawn line connects all points having a certain value of *r*. Two dotted lines have been drawn for constant degree of saturation ($p = 0.4$ and $p = 0.8$, according to the definition of the C. I. E. 1948). It is seen that in a normal painting the saturated colours (colour points near the curve of the spectral colours) can only be obtained with lower brightnesses than white (saturation 0, colour point *B*).

A fluorescent pigment, on the other hand, owes its colour to the fact that it re-emits the absorbed radiant energy with a specific spectrum. The efficiency of the energy conversion, thanks to the progress made in preparative chemistry, is nowadays very high (quantum efficiency about 80 %) and practically independent of the spectrum of the fluorescent light. With a given intensity of ultra-violet light a pigment with a highly saturated fluorescent colour (narrow emission spectrum) will therefore, as far as energy is concerned, roughly speaking be able to emit just as much as a white fluorescent pigment having an emission spectrum covering the whole of the visible wavelength range or large parts thereof. If the narrow emission band of the first-mentioned pigment lies near the maximum of the relative visibility curve (5550 Å, in the yellow-green) then the energy supplied produces a very high brightness, whereas the white fluorescent pigment must of necessity emit part of the available energy in less favourably situated spectral ranges and thus lose in brightness. This is clearly demonstrated by the spectral distribution curves given in *fig. 3* for three oil pigments and three roughly corresponding fluorescent pigments.

It is fully in line with this reasoning that the value of 130 mentioned above for the brightness range of the fluorescent picture was found by comparing the darkest black with the brightest (not so very saturated) green. A comparison between black and white led to the smaller factor of 100. These figures confirm what the eye immediately sees when looking at the picture: it is the "radiant" saturated colours, together with the great range of brightness, which lend the typical character to the picture.

After what has been said above it is hardly necessary to point out that the reproduction in fig. 1*a* is incapable of fully representing the impression produced by the fluorescent picture. The brightness range of such a reproduction is in fact

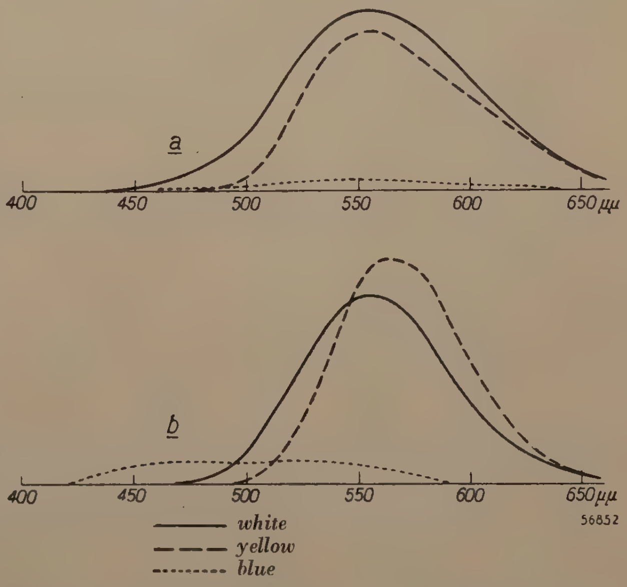

Fig. 3. *a*) The spectral distribution of the reflection has been measured for three normal oil paints, white, yellow and blue. For each wavelength the product of the spectral reflection coefficient and the relative visibility factor has been plotted. Thus the area underneath each curve gives a direct measure for the brightness (for exposure under a light source with uniform energy distribution, standard illuminant *E*). The curve for "white" is everywhere higher than the other curves and thus also has the largest area. The differences in the trend of the curves are but slightly pronounced, the colours not being highly saturated.

b) The same for three fluorescent pigments with about the same colours, white, yellow and blue. The product of the spectral emission coefficient and relative visibility factor has been plotted. Both the curve for yellow and that for blue lie in part higher than that for white. The colours are more highly saturated than in (*a*), but at the same time they are brighter in proportion to the white. The curve for yellow has even a larger area than that of white.

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4) A clear explanation of this is given in P. J. Bouma, Physical aspects of colour, Philips Techn. Library, publ. Meulenhoff, Amsterdam 1946; see sections 46 and 47.

still less than that of a normal painting, usually not more than 10 to 12. As regards the high relative brightness of the saturated colours, this property can be found to a certain extent in the reproduction when all the "natural" white (and also all shining objects or surfaces) are covered over or removed from the surroundings of the reproduction. If this is not done, then by comparison with the natural white the brightest "white" in the reproduction will give a greyish impression and the characteristic feature of the saturated colours will escape notice.

By taking the same precautions the effect of a bright, saturated colour can be obtained also in the normal techniques of painting: all the white must be purposely tempered. The effect of this can be very striking in the art of glass-painting, where conditions are favourable for avoiding the undesired impression mentioned, namely that the observer notices only the tempering of the white: the light source is behind the stained-glass window and, provided the window does not contain any non-painted or too bright panes, the surroundings are automatically sufficiently tempered. Moreover, tempering of the white in the painting, which with the normal painting techniques would constitute a further unpleasant limitation for the already small range of brightness, is very easily acceptable in glass paintings, as transparent pictures have the property that their brightness range may be much greater than that of pictures viewed in reflected light [5]).

This two-fold similarity, of great brightness range and, in the case of some windows, radiant deep colours, accounts for the fact that when viewing the fluorescent painting most observers remark that the effect reminds one very much of that of a stained-glass window. The broad black lines dividing up the plane, intended to demonstrate the great contrast obtainable between light and dark, undoubtedly help to create the suggestion of a window with leaded panes.

Let us now turn to the technique of painting with fluorescent paints.

In *table III* is a list of the fluorescent powders that were used in the painting of the picture concerned. They were all chosen from the zinc-cadmium-sulphide system with silver as activator, that is of the type $[x\,\mathrm{Zn}.(1-x)\,\mathrm{Cd}]$ S-Ag, with different proportions $x:/(1-x)$ of zinc and cadmium. The spectral distribution of the fluorescent light from this system shows a fairly sharp maximum, the position of which (wavelength $\lambda_{\max}$) can be varied within wide limits by the selection of x, as may be seen in the table.

The number of basic colours used may seem to be small compared with the enormous variety of paints available to the painter for instance in the normal oil-painting technique. This limitation, however, was quite voluntaiy. By a further variation of x and the use of still other fluorescent systems the number of basic colours could be increased at will and it would be easy to compete with the wealth of oil paints. But even the largest possible variety of basic colours will not relieve the painter of the necessity to produce intermediate tints by mixing the paints. Only then can he hope to reproduce the infinitely varying tints occurring in nature to make every stroke of the brush harmonize perfectly with the whole and to create that "vibration" of the colour, so indispensable to give life to every part of the picture. Since, therefore, mixing is unavoidable, the number of basic colours to be used is mainly a question of convenience, of custom and perhaps of individual style. Few artists use more than 20 or 30 oil paints, whilst some purposely use no more than 10 or even less. For a first acquaintance with the new technique the small number of fluorescent pigments given in our list proved to be quite sufficient.

Table III. Fluorescent pigments used for painting the picture. All are of the system $[x\,\mathrm{Zn}.(1-x)\,\mathrm{Cd}]$ S-Ag and each pigment is thus characterized by the value of x. The peak of the spectral distribution of the fluorescence of each pigment lies at the wavelength $\lambda_{\max}$.

x	Colour of the fluorescence		Colour in daylight
	$\lambda_{\max}$ (mμ)	colour	
1.00	460	blue	white
0.85	492	green-blue	white
0.77^5	514	green	white
0.68	541	yellow-green	white
0.58	570	yellow	light-yellow
0.50	600	orange	medium yellow
0.39	630	orange-red	yellow
0.33	655	red	orange

Although the mixing of paints thus is a normal routine to the artist, when he comes to mix fluorescent paints he finds there are several unexpected peculiarities. In the first place the mixing is not subtractive, as is the case with all other techniques of painting, but additive.

Of course this fact in itself is not new, but in this connection it is perhaps worth while considering it more closely.

In water-colour painting the paints to be mixed are applied one after the other in thin transparent layers at the desired place. The incident light passes through all the layers in succession and is then reflected back through the layers again (*fig. 4a*). In each layer the light undergoes the selective absorption which determines the visible colour of that layer, so that ultimately only those parts of the spectrum in the emerging light remain which are not appreciably absorbed by any of the layers. This is subtractive mixing. With pastel colours conditions are slightly different. Different coloured chalks (grains of chalk with adsorbed grains of pigment) are applied to the paper and thoroughly mixed by rubbing, for instance with the finger. A ray of light falling on the drawing is reflected (scattered) several times in the microscopic accumulation of coloured grains on a particular spot before emerging from the paper again (fig. 4*b*). With each grain the spectrum is weakened in a certain part by the selective reflection determining the colour of that grain, and the emerging light contains only those parts of the spectrum that have not been absorbed by any of the kinds of grain which it has encountered. Thus here, too, we have subtractive mixing, each component contributing towards the ultimate colour by subtracting certain parts of the spectrum. In mixing oil paints the position is rather similar to that existing with pastel colours, except that the mixing is more complete owing to the suspension of the extremely small grains of pigment in the linseed oil; the mixed colour may therefore be more homogeneous.

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[5]) This fact is well-known in photography, where one can count on a maximum brightness range of about 30 for positive prints on paper and one of 100, or in some cases even 1000, for transparencies.

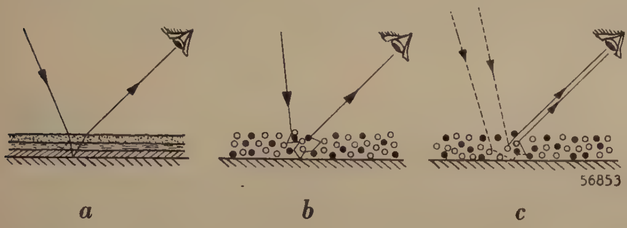


Fig. 4. *a*) In water-colour painting a mixed colour is obtained by applying different transparent layers of paint one on top of the other, each of which reduces a specific part of the spectrum in the transmission of the light: subtractive mixing. (Each layer consists in fact of innumerable grains of pigment; for the sake of clarity this is not indicated here.)

b) In pastel drawing one likewise has subtractive mixing: each ray of light undergoes a number of reflections from the grains of the chalks mixed together, each kind of grain weakening a specific part of the spectrum. The situation is somewhat similar also in oil painting; the pigment grains themselves are mixed in a suspension, the light is scattered in the grains and thereby selectively attenuated before diffusing outwards.

c) In the case of painting with fluorescent paints a mixed colour arises, owing to the radiation emitted from grains of a different kind impinging upon the same element of the retina: additive mixing. The ultra-violet rays falling upon the layer of paint are indicated by dotted lines.

The situation in the case of a mixture of fluorescent pigments resembles that of oil-paints. There is a microscopic accumulation of pigment grains, in this case with different colours of fluorescence (fig. 4*c*). The incident ultra-violet rays are absorbed by the grains, each one of which then radiates its own specific colour, and after being scattered again by other grains these coloured light rays emerge. With many fluorescent substances the grains are "white" (see the first lines of table *III*), that is to say their absorption of the visible light is not selective. The coloured light rays then emerge unaltered and where different kinds of light reach the same spot of the retina the eye adds up all the individual spectral contributions. This is the essence of additive mixing. If the pigments are not completely white (see the last lines of table *III*) we get a sort of blending of additive and subtractive mixture.

In the case of additive mixing the colour point of the resultant colour in the chromaticity triangle can easily be predicted from the colour points of the components; *fig. 5a* serves to remind us of this. For subtractive mixing there is no such simple law (except in a few special cases; cf. fig. 5*b*). This does not mean to say, however, that additive mixing would be easier for the artist than subtractive mixing. The contrary is true. For mixing, such as he is accustomed to, the artist does not rely upon any physical law but works according to a series of rough rules, the product of his own experience and that of others. These rules of course do not hold for additive mixing. Thus, the painter is astonished when in the mixing of say a yellow and a blue fluorescent paint he does not get green, as would be the case with normal paints, but a highly unsaturated, perhaps pink or even white tint (see fig. 5*a*). Mixing will therefore continuously give rise to surprising results, at least until one gets accustomed to the mixing of these paints.

We may mention a second unexpected technical problem that occurred in painting the fluorescent picture. In order to apply the pigments durably to the canvas they must be dispersed in a binding agent. This binding agent must not be fluorescent, it must not cause any chemical reaction in the fluorescent substances and, furthermore, it must possess all the various properties required of a paint vehicle. More or less by chance, normal linseed oil as used in oil-painting also proves to fulfil the former conditions fairly well, and this was therefore chosen as the binding agent. Now, in the usual oil-painting technique, if a pigment is coarse-grained it is first ground very fine and then mixed with the linseed oil to a paste. The very fine grinding gives normal paints a good covering power and at the same time two or more suspensions of paint obtained in this way can very easily be mixed, resulting in a highly uniform tint. Fluorescent pigments of the system used must not, however, be ground to a fine grain, because this results in a loss of the light yield! Consequently, in order not

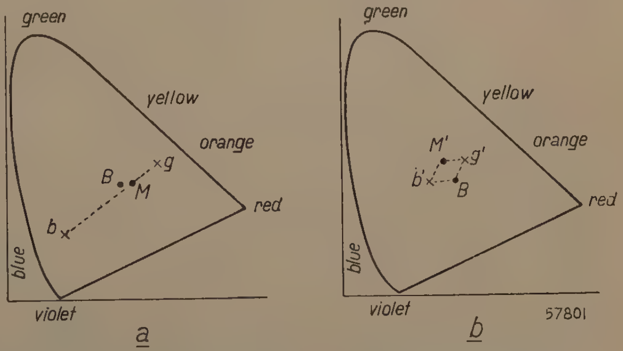


Fig. 5. *a*) Additive mixing of two colours represented in the chromaticity triangle by the points g and b. The colour point M of the mixture lies on the line through g and b; in the case drawn here (g a yellow, b a blue colour) by mixing in suitable proportions one can get the mixed colour near the white point B.

b) There is no general law for subtractive mixing. For certain simple cases there are approximate rules. If, for instance, two fairly unsaturated colours are mixed, such as g' and b', the colour point M' of the mixed colour is found approximately as the fourth corner of the parallelogram $Bg'b'M'$ (cf. H. E. J. Neugebauer, thesis Dresden 1935).

to sacrifice too much of the beautiful effect of fluorescent paints, one has to work with suspensions of fairly coarse grains, and in mixing such suspensions special precautions must be taken: it is advisable first to sort the powders according to the size of crystal and to mix only those paints that have practically equal crystal sizes. If this precaution is not taken then, probably owing to differences in the rates of sedimentation of the particles of different size, when the paint is being applied to the canvas the mixed components have a tendency to separate.

In principle this difficulty can be overcome by selecting or specially preparing fluorescent substances which without grinding already have the desired very fine structure found with normal paints (size of grain, for instance, 20 μ). The effect of grinding upon the light yield, which causes the said complication, can, on the other hand, be turned to advantage for shading down colour spots where such is desired. In the normal techniques this can be done by admixing some black (or other dark colour) and for a fluorescent picture one could similarly dilute the paint suspension with "black", i.e. non-fluorescent substances, such as for instance common white (!) chalk. Tempering by using a pigment that has been ground, however, gives a more homogeneous impression.

Finally a few words must be said about other practical questions which arise in the new technique. In order to avoid photo-chemical dissociation, as a result of which the "luminosity" of the picture would in course of time diminish, it is important that the crystals should be well protected against moisture. The embedding of the crystals in the linseed oil vehicle is favourable in this respect, and in addition the completed picture can be sprayed with a covering layer of zapon lacquer (which is also non-fluorescent). The backing, as already stated, was ordinary artist's canvas treated with white chalk (again non-fluorescent materials). In daylight the white fluorescent pigments thus stand out only slightly against the background and the form of what is represented in the picture can only be seen faintly (cf. fig. 1*b*). Consequently when the source of ultra-violet radiation is switched on the metamorphosis is all the more surprising, but on the other hand there is the drawback (in addition to the limitation of the brightness range already referred to) that some of the effect is very soon lost if any visible light falls on the picture. If the presence of a tempered visible lighting is to be allowed for, it is better to use a backing that is black (i.e. black also in daylight).

It almost goes without saying that while one is painting the canvas may exclusively be exposed to the light from the mercury lamp (with its filter). The subject, on the other hand, — if one is painting from nature — must be normally lighted. To keep the lighting of the canvas separate from the lighting of the subject is a somewhat unusual problem for the artist and one that is certainly not always easy to solve.

The filter in front of the mercury lamp suppresses not only the visible light but also the short wavelength ultra-violet, i.e. the strong mercury line of wavelength 2537 Å. It is almost exclusively the mercury line of wavelength 3650 Å that is responsible for exciting the fluorescence. Irradiation with this wavelength has practically no effect upon the skin, so that there is no fear of suffering from erythema on the hands even when working on the canvas for long periods under the mercury lamp.

May the experiment described and the experience communicated here induce painters to try out themselves the possibilities of the new technique.

Summary. One of the authors (J. H. L. J.) has painted a picture with fluorescent paints. The pigments — 8 different ones chosen from the system of zinc-cadmium-sulphide with silver as activator — were mixed with linseed oil; the canvas was ordinary artist's canvas treated with white chalk; the finished picture was sprayed with zapon lacquer. All these materials fulfil the requirement that they themselves should not show any fluorescence. When preparing intermediate colours from two or more fluorescent pigments one is dealing with additive mixing; the rough mixing rules which the artist usually applies and which are based on subtractive mixing do not hold here. The fluorescent powders used in this experiment presented some difficulty in the mixing because they had to be used in the form of rather coarse grains; grinding these pigments would cause a loss of light yield. — The artistic value of painting with fluorescent pigments lies, in the opinion of the authors, in the great brightness range thereby attainable; this is very much greater than the maximum obtainable by the normal techniques of painting, as is proved by actual measurements. Moreover, the fluorescent picture shows exceptionally bright saturated colours, some even brighter than the brightest white, a property due to the fact that the yield of light conversion is practically the same for all fluorescent pigments. A large brightness range and "radiant" colours are likewise found in some stained-glass windows, to which the fluorescent painting therefore shows a striking resemblance.

THE MEASUREMENT OF CHANGES IN LENGTH WITH THE AID OF STRAIN GAUGES

by A. L. BIERMASZ and H. HOEKSTRA.

621.317.39:630.172.222

For some decades the technique of measuring electrical quantities has been ahead of that for the measurement of other, e.g. mechanical, quantities, as far as sensitivity and convenience are concerned. This advance has been further augmented by the development of amplifiers, cathode-ray oscillographs and the like. It is therefore obvious that this advanced technique should also be made available in other fields of measuring by means of instruments designed for converting non-electrical into electrical quantities. An example of such an instrument is the strain gauge dealt with in this article, which shows differences in resistance when its length is changed, which can be measured electrically. In engineering there are wide fields of application for strain gauges in combination with a measuring bridge and/or a cathode-ray oscillograph.

A fundamental problem in the dimensioning of any mechanical construction is the distribution of stresses arising under different conditions of loading. Only with the knowledge of this distribution of stresses — together with the necessary knowledge of the properties of materials — can one arrive at the ideal construction which is nowhere too weak nor anywhere unnecessarily strong.

However, if the construction is complicated great difficulties are encountered in calculating the distribution of stresses. One must therefore often resort to practical measurements on existing constructions (or models). Usually measurements can only be taken on the surfaces, but it is just there that the stresses are as a rule greatest. As a measure for the stress in for instance a rod or bar under a tensile load one takes the change in length of the rod, for as long as the deformation is elastic, it is proportional to the stress. In more complicated cases the stress can be deduced from the changes in length measured in two or three directions.

For carrying out these measurements there are extensometers with which it is possible to determine the changes taking place in the distance between two suitably chosen points of the construction when the load acting upon it varies. In order to measure this change in distance with sufficient accuracy either mechanical or optical extensometers are employed which magnify the movement with the aid of a set of levers or by optical means before the actual measurement is made.

For simple cases with a static load these extensometers are quite practicable, but they are of no use with more complicated constructions, in places difficult to get at or where vibrations that are not of a very low frequency must be accounted for. We have only to take as an example aircraft construction, where variations in length have to be measured during the flight, often at some hundreds of points at the same time, on the wings, fuselage and tail planes, whilst moreover large vibrations may be superimposed on the static load. In such cases the solution of the problem is offered by what are known as strain gauges, with which variations in length are measured by electrical means, this method possessing, moreover, advantages over extensometers.

Principle and advantages of strain gauges

It has been known for some time that the electrical resistance of a wire changes with the mechanical stress in the wire; Lord Kelvin described this phenomenon as far back as 1856. This forms the fundamental principle of strain gauges, since these consist of a wire which is glued onto the constructional element under test in such a way that it undergoes all the changes in length taking place in that part of the structure. The measured resistance variations of the wire then give a measure of the change in length. It is only during the last ten years, however, that in several countries strain gauges have been developed with a sufficient degree of reliability.

The main reasons why the method of measuring with strain gauges has come to be so widely applied are the following:

1. The gauges are only a few centimetres long and can thus be applied in places which would otherwise be almost inaccessible.
2. The measuring instrument proper is set up at a distance and if desired can be connected successively to a large number of strain gauges.
3. By this method also dynamic loads (vibrations) can be measured.

4. In combination with an oscillograph it is possible
   - *a*) to record the observations photographically,
   - *b*) to observe and record simultaneously the resistance variations of two or more strain gauges.

Construction, components and use of strain gauges

Fig. 1a is a sketch of the larger of the two types of strain gauges made by Philips. It consists of a resistance wire of constantan (55 % Cu, 45% Ni) bent in zig-zag fashion and glued onto a paper carrier. By means of this carrier, when glued onto the object to be tested, the variations in length of the object are faithfully translated in the wire, whilst at the same time the carrier provides electrical insulation. Connected to each end of the constantan wire by a soldered joint is a copper lead which is also partly glued onto the paper carrier, thereby providing sufficient safeguard against any strain on the leads being transmitted to the thin constantan wire. The resistance of this gauge is 600 ohms.

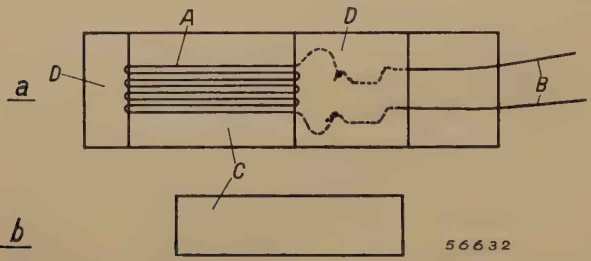


Fig. 1. *a*) Sketch of the strain gauge GM 4472. *A* = resistance wire, *B* = leads, *C* = paper carrier (actual size), *D* = paper covering strips. *b*) Carrier of the strain gauge GM 4473 (actual size).

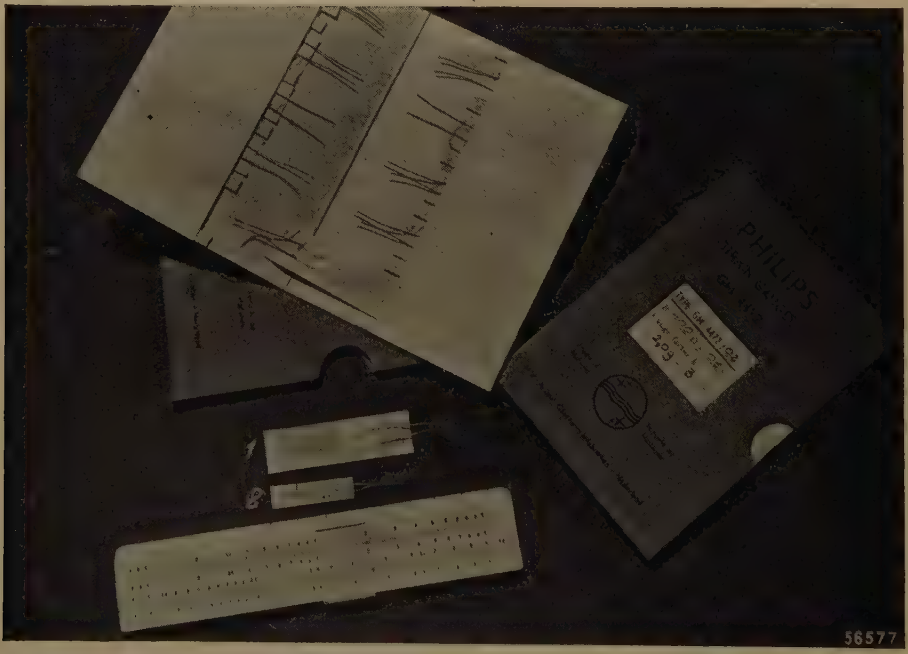
The smaller type (GM 4473, fig. 1*b*) is of a similar construction but has a resistance of 120 ohms. Owing to its smaller dimensions it can be applied in even less accessible places more easily than the larger type (GM 4472), which, however, with its larger surface, can dissipate a greater power, thus allowing of more sensitive measuring.

Fig. 2 shows a specimen of each of the two types and the cases in which the strain gauges are supplied in packets of 10. The frequency range of the vibrations covered by the strain gauge extends to above 10,000 c/s.

We shall now discuss first the principal components of the strain gauge: the resistance wire, the glue and the paper carrier, and then the method of gluing.

The resistance wire

Since the relative resistance variation, even with the greatest elongation occurring, is only small (in the order of 0.1%), one has to guard against the effect of accidental resistance variations that may occur for instance in switches or in the long connections often necessary between the strain gauge and the measuring instruments. It is therefore essential that the resistance of the strain gauge should be at the least in the order of 100 ohms. In order to get



Figl 2. *1* = strain gauge GM 4472, *2* = strain gauge GM 4473; also the two cases in which the strain gauges are sold.

such a resistance in the strain gauge only a few centimetres long with a reasonably robust wire, a material has to be used which possesses a high specific resistance. This excludes the pure metals and leaves only alloys like constantan and chromium nickel, and carbon.

In the second place the choice of material for the wire is determined by the behaviour of the gauge factor k, that is the ratio of the relative variation $\Delta R/R$ of the resistance to the relative variation $\Delta l/l$ of the length:

$$k = \frac{\Delta R}{R} : \frac{\Delta l}{l} = \frac{\Delta R}{R} \cdot \frac{1}{e}.$$

($\Delta l/l = e$ is also called the elongation.) The greater the value of k (absolute), the higher is the sensitivity of the measurement, but a linear relation between $\Delta R/R$ and e (i.e. a gauge factor which is independent of the amount of the elongation) is even more important.

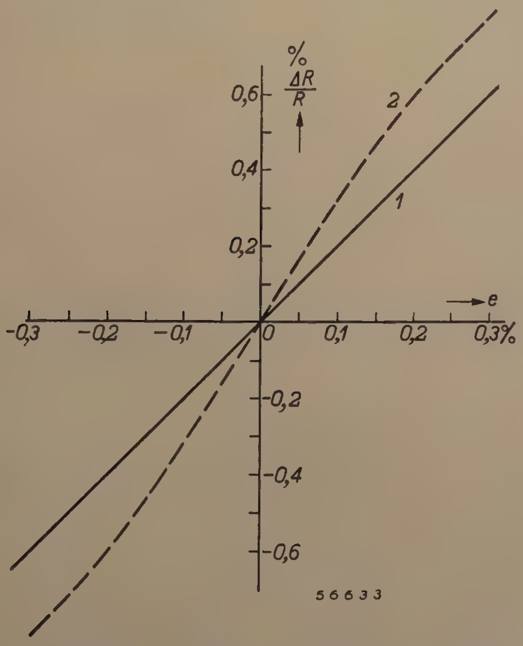


Fig. 3. The relative resistance variations $\Delta R/R$ as function of the elongation e, (*1*) for constantan, (*2*) approximate curve of a non-linear relation as found with chromium nickel.

The high k value found with carbon (about 20), which is due to the changeability of the transfer resistance between the particles of carbon, makes it tempting to use this material in strain gauges [1]), but the results in the long run are not sufficiently reproducible and as a consequence carbon is not used as a material for the resistance element any more.

The relation between $\Delta R/R$ and e for constantan is represented by the continuous line in *fig. 3*. This relation is practically linear, with $k \approx 2$ both in the elastic area (e between $\pm 0.2\%$) and outside it. With other alloys having a high specific resistance this relation is a non-linear one: chromium nickel for instance gives a value of $k \approx 3$ for a small elongation, this value dropping to about 2 in the plastic area, as roughly indicated by the broken curve in fig. 3. This non-linear characteristic is a great disadvantage in practice and explains why constantan is preferred.

The resistance of a conductor varies not only with the elongation but also with the temperature. Where only a rapidly changing elongation has to be measured (vibrations) gradual variations in resistance due to temperature fluctuations are not disturbing, but in the case of static loads they may well be so. We shall presently discuss a method whereby the influence of temperature is compensated, but it is nevertheless desirable that the temperature coefficient (α) of the strain gauge should be as small as possible. In this respect, too, constantan is highly favourable, α being in the order of 1×10^{-6} compared with about 100×10^{-6} for chromium nickel.

In *table I* the quantities discussed are listed for constantan, chromium nickel, carbon and, for comparison, a pure metal (iron).

Table I. Approximate values of the specific resistance ϱ, the gauge factor $k = (\Delta R/R) : e$ (within the limits of elasticity) and the temperature coefficient α of the resistance of some materials.

Material	ϱ μΩ·m	k	α 10^{-6} (°C)$^{-1}$
Iron	0.1	–4	5000
Constantan	0.5	2	1-3
Chromium nickel	1	3	100
Carbon	70	20	–500

Here we can go rather more deeply into the value of the gauge factor k of metals.

The resistance of a wire with diameter D is:

$$R = \frac{l\,\varrho}{\frac{\pi}{4} D^2} \qquad (1)$$

When the wire is stretched (or compressed) not only l changes but also D and ϱ. As regards the change in diameter Poisson's relation applies:

$$-\frac{\mathrm{d}D}{D} : \frac{\mathrm{d}l}{l} = \mu,$$

in which for most metals, in the elastic area, $\mu \approx$ 0.30-0.35. As regards the specific resistance ϱ it is known that when a metal is subjected to compressive forces from all sides ϱ changes with the density, thus with the volume V. In the case of constantan we then have the linear relation

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[1]) See for instance S. L. de Bruin, The investigation of rapidly changing mechanical stresses with the cathode-ray oscillograph, Philips Techn. Rev. 5, 26-28, 1940.

$$\frac{\mathrm{d}\varrho}{\varrho} : \frac{\mathrm{d}V}{V} = c, \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

with $c = 1.13$. We shall assume, as Opechowski does, that this relation also holds for extension and contraction. Since $V = {}^1/_4\pi D^2 l$ equation (1) can be written as follows:

$$R = \frac{\varrho l^2}{V}.$$

By differentation we arrive at

$$\frac{\mathrm{d}R}{R} = \frac{\mathrm{d}\varrho}{\varrho} + 2\,\frac{\mathrm{d}l}{l} - \frac{\mathrm{d}V}{V} = 2e + (c-1)\,\frac{\mathrm{d}V}{V}. \quad . \quad (3)$$

Plastic deformation is characterized by constancy of the volume, hence for all materials (even if eq. (2) does not hold) the rule applies that

$$\frac{\mathrm{d}R}{R} = 2e,$$

or

$$k = 2,$$

in accordance with experiment.

With elastic deformation on the other hand

$$\frac{\mathrm{d}V}{V} = 2\,\frac{\mathrm{d}D}{D} + \frac{\mathrm{d}l}{l} = (1-2\mu)\;e,$$

so that (3) becomes

$$\frac{\mathrm{d}R}{R} = 2e + (c-1)\,(1-2\mu)\;e,$$

or

$$k = 2 + (c-1)\,(1-2\mu)\,.$$

For constantan, with $c = 1.13$ and $\mu = 0.325$, this works out to

$$k = 2 + 0.13 \times 0.35 = 2.05,$$

which falls within the extreme values measured (2.09 ± 0.06). It must be said however that with other materials the agreement is much less satisfactory.

The glue and the paper

The paper carrier and the glue used for fixing the constantan wire on the carrier and the latter to the object to be tested have to translate the deformations of the object faithfully to the wire. Consequently the adhesive strength of the glue must be exceptionally high. The best kinds of glue are those having a cellulose base and consisting of long molecules with numerous polar atom groups. It is the latter which result in the strong adhesion (both to paper and to metal) and, moreover, show practically no after-effects (creep).

After-effects in a strain gauge constitute a most undesirable property, because then the unambiguous relation between resistance variation and deformation is lost. Both in the wire as well as in the glue and the paper after-effects must therefore be kept small in comparison with other inaccuracies in the measuring method. This is a requirement that is particularly difficult to meet as regards the glue, but in the manufacture of the Philips strain gauges this has been satisfactorily met. With an elongation of 0.1% for instance the permanent relative resistance change is normally less than 10^{-5}.

The long molecules of cellulose glue have the property of adapting themselves somewhat to the direction of the elongation, thus lending great toughness to the adhesive layer. Other kinds of glue on the other hand become more or less brittle (for instance polysterene, which moreover is less polarized than cellulose glue).

Finally the glue must not take too long to dry; this we will refer to farther on when dealing with the method of gluing .The thinner and more porous the paper, the quicker does the glue dry, and for this reason the thinnest possible paper is used for the Philips strain gauges, having regard to insulation and the necessity for the gauge to remain flat.

For gluing strain gauges onto the objects to be tested, Philips have placed on the market tubes of glue (GM 4479) which can be used at temperatures up to 60 °C.

Gluing on the strain gauges

In order to ensure proper adhesion of the strain gauge to the object being tested, at the place where it is to be applied the metal must be thoroughly cleaned first with emery paper and then with some grease-remover, for instance pure acetone. The cleaned surface must not then be touched with the hands. A thin layer of glue (GM 4479) is then spread out over it and when this is dry the back of the strain gauge is likewise covered with a thin layer of glue and pressed down on top of the other layer, taking care that the longitudinal axis of the strain gauge coincides exactly with the direction of the deformation to be measured.

After about 6 hours the glue is dry enough and the adhesion is sufficient for taking rough measurements with the strain gauge. For accurate measurements, however, particularly when they are to be of a long duration, the glue should be allowed to dry a few days, preferably while heating to 70 °C. Even after that every possible precaution should be taken to exclude moisture, since moisture has a serious effect upon the measuring results, due to two causes: variable insulation resistance and variable mechanical stress both in the glue and in the paper. As regards the insulation resistance, if for instance with a strain gauge of 600 ohms it is desired to measure resistance variations of 0.1% with no greater error than 1% then the insulation resistance (in parallel with the strain gauge) would answer high demands of constancy if it were only in the order of 60 megohms. If, on the other hand, it is of the order of 1000 megohms, as is to be reached with the above-mentioned measures, then great changes in the insulation resistance are harmless.

In the second place moisture causes local swelling of the glue and of the fibres of the paper. Even in a glued-on strain gauge, which is not free to expand, such deformations are apt to arise and cause perceptible, irregular resistance changes.

Precision measuements of long duration should not be begun until the insulation resistance has reached 500 MΩ. The gauge must then be shut off from the air either with a layer of wax or with a sheet of rubber glued round the gauge and enclosing at the same time a moisture-absorbing substance (silica gel). This latter method has been developed in the Laboratory for Applied Mechanics of the Foundation for Technical-Industrial Research ("T.N.O.") at Delft (Netherlands), with which institution we are fruitfully cooperating in this field. It is a method that has proved to be very satisfactory, even when taking measurements over a long period in the open air in rainy weather.

The measuring apparatus

We shall now proceed to discuss the apparatus employed for measuring small resistance variations. A Wheatstone bridge where one branch is formed by the strain gauge (G_1 in *fig. 4*) is suitable for this, though in some cases, as will be shown presently, a simpler system may also answer the purpose. The bridge circuit, however, is to be preferred whenever the influence of temperature has to be excluded. The following will show what this effect is.

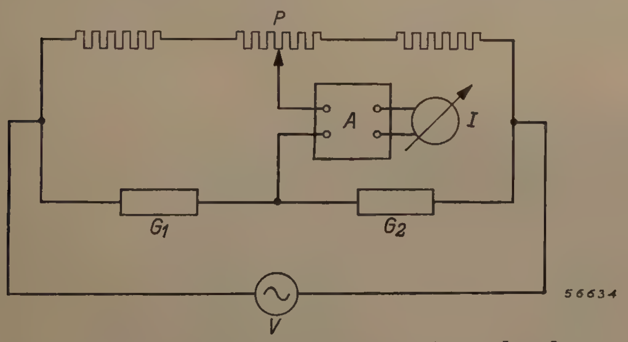

Fig. 4. Wheatstone bridge with an active and a dummy gauge (G_1 and G_2). V = alternating voltage supply, P = potentiometer for balancing the bridge, A = amplifier, I = indicator.

The effect of temperature

When the temperature of the object to which the strain gauge is affixed changes while the measurements are being taken this may lead to two errors:

1) The resistance variation observed in the strain gauge is partly due to the temperature coefficient of constantan, small as it may be; this part of the variation must not be interpreted as a deformation.
2) Even in the absence of stresses the object undergoes deformation, namely thermal expansion, which it is not as a rule desired to measure but which shows itself as a variation of the resistance of the strain gauge because of the usually different expansion coefficient.

Both these errors can for the greater part be avoided by using a compensating or dummy strain gauge in the bridge circuit. This is a strain gauge of the same type as the "active" or primary gauge G_1 (fig. 4); it forms an adjacent branch of the bridge (G_2). It is glued onto the same material as G_1 but this piece of material is not mechanically loaded, and the dummy gauge has to be placed close enough to the actual measuring point so that it undergoes the same temperature variations as the active strain gauge. Thus the active and the dummy gauges are subject to the same thermal influences. The resistance variations resulting cancel each other in the bridge circuit, so that only the variations which correspond to mechanical stresses in the object are measured.

Often it is possible to fix the dummy gauge in such a way that it not only compensates the thermal effect but also contributes towards the unbalance of the bridge, so that the measuring system becomes more sensitive. In such a case the compensating gauge is fixed at a place on the object where the material is subject to contraction while the "primary" gauge undergoes an elongation, or vice versa. We shall come across some examples of this farther on.

The two types of measuring bridge developed for use with strain gauges have both been designed for working with a compensating gauge.

We shall now consider the measuring bridges more closely.

Measuring bridge for static load

The diagram of fig. 4 represents the principle of both types of measuring bridge. Before the active gauge (G_1) is deformed, the bridge is balanced with the aid of the potentiometer P, that is to say, the deflection of the indicator I is set to zero. In order to increase the sensitivity the indicator is preceded by an amplifier. So as not to complicate the latter the bridge is not fed with D.C. but with an alternating voltage (derived from a valve oscillator incorporated in the apparatus).

Owing to an alternating voltage being used, the bridge must also be balanced capacitively. The measures taken for this are not indicated in fig. 4 and we shall not go into them here.

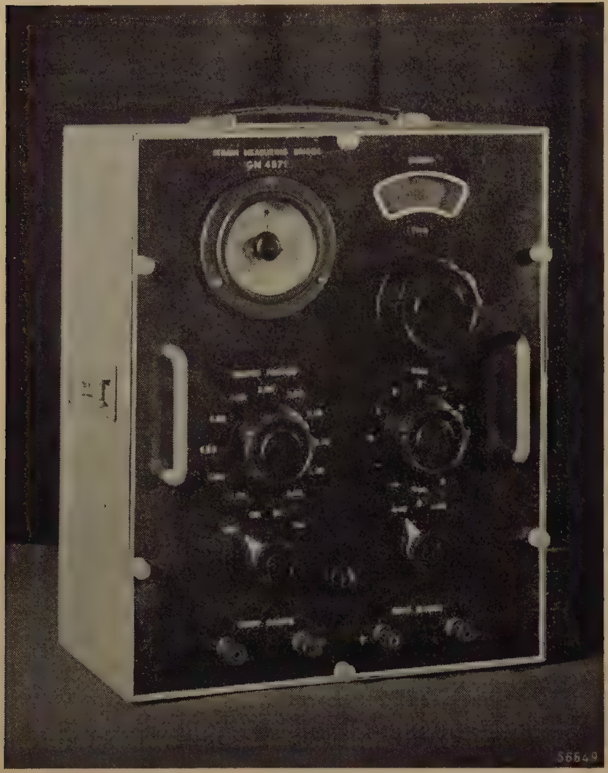

Fig. 5. Measuring bridge (GM 4571) using the zero method for measuring static loads. *To the right*, one above the other, three knobs for balancing the bridge; *to the left*, from top to bottom, the indicator, the correcting knob for the gauge factor of the strain gauge, and the knob for switching on and off, acting at the same time as the switch by means of which the indicator can be used for checking the batteries.

Deformation of the active strain gauge will throw the bridge out of balance. As is known, one can then proceed in two ways:

a) rebalance the bridge with the potentiometer *P* and determine the resistance variations from the two positions of *P*;

b) use the deflection of the indicator as a direct measure of the resistance variation of G_1.

The measuring bridge of the type GM 4571 (*fig. 5*) works on the zero method mentioned sub (*a*). This has the advantage that the result is independent of the degree of amplification, but on the other hand it is of course limited to static load only.

The potentiometer is provided with a scale from which the elongation can be read directly. In order to allow for the fact that there is a slight difference in the gauge factor *k* as between one strain gauge and another, a correction knob is provided which has to be previously set in the position corresponding to the gauge factor of the strain gauge used. This factor is shown on the strain gauge case (fig. 2).

As indicator a moving-coil meter is used, which is connected via selenium rectifiers [2]) to the output of the amplifier, and the indicator can be used at the same time as a voltmeter for checking the batteries feeding the oscillator and the amplifier. These batteries make the bridge particularly suitable for taking measurements in places where no A.C. mains are available.

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[2]) J. J. A. Ploos van Amstel, Small selenium rectifiers, Philips Techn. Rev. **9**, 267-276, 1947.

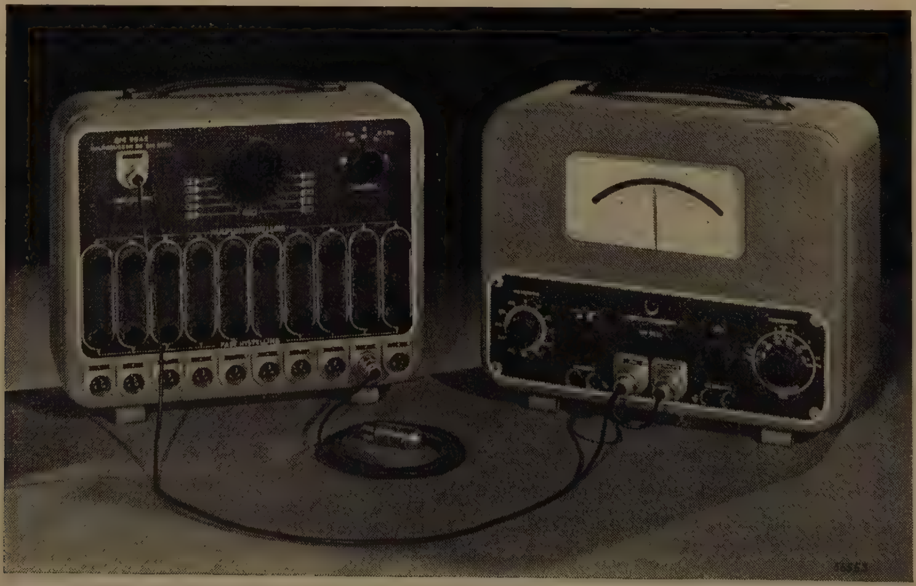

Fig. 6. *On the right* the measuring bridge GM 5536 for measuring static and dynamic loads. The elongation can be read directly from the meter. The amplified output voltage from the bridge can be applied to an oscillograph. *On the left* the switch GM 5545 with which the bridge can be connected successively to any one of 10 pairs of strain gauges.

This bridge is suitable for use with strain gauges of more than 100 ohms resistance.

Measuring bridge for static and dynamic loads

The measuring bridge of the type GM 5536 (*fig. 6*) is used in the manner indicated above under (*b*).

This bridge has to be balanced before starting to take measurements. When the balance is disturbed it produces an output voltage which in the case of dynamic load is a modulated alternating voltage; the "carrier" of the oscillator feeding the bridge is modulated with the frequencies of the mechanical vibrations. With the aid of a ring modulator [3]) consisting of four selenium rectifiers, the output voltage is demodulated and converted into a rectified voltage which is fed to a moving-coil meter acting as indicator. Static load is to be regarded as a special form of dynamic loading where the frequency of the vibrations is zero. Both for static and for dynamic loads the deflection of the meter is a measure of the resistance variation of the strain gauge.

Instead of the meter, a cathode-ray oscillograph can be used as indicator. By this means the vibrations can be visualized and if necessary recorded photographically. In order to avoid distortion an oscillograph should be used which has an amplifier suitable for the very low frequencies that may occur with mechanical vibrations. Such an oscillograph is for instance the type GM 3156 [4]), which is suitable for frequencies down to 1 cycle per second.

As an accessory for the measuring bridge GM 5536, which is intended for use with strain gauges of 600 ohms (and if need be higher), a change-over switch is provided (fig. 6), by means of which the bridge can be quickly connected in succession to 10 different combinations of an active and a dummy strain gauge. The change-over switch is provided with a device by means of which the meter or the oscillograph can be calibrated.

A cathode-ray oscillograph offers the possibility of visualizing simultaneously the resistance variations of two or more strain gauges, so that time and phase differences of the vibrations can be determined. For that purpose one or more electronic switches [5]) can be used.

Circuit for an exclusively dynamic load

If measurements have to be taken only under a dynamic load then no account need be taken of gradual variations due to temperature fluctations. In that case a compensating strain gauge and a bridge circuit are superfluous and one can manage quite well with the simple arrangement illustrated in *fig. 7*, where the strain gauge is connected to a battery via a resistor. Resistance variations of the strain gauge set up across its terminals voltage variations which are applied to an oscillograph via a pre-amplifier.

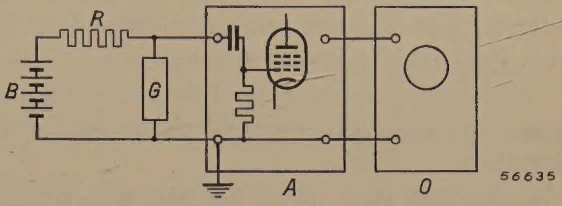

Fig. 7. Circuit for measuring dynamic loads. B = battery (45 V), R = series resistor, G = strain gauge, A = pre-amplifier, O = oscillograph.

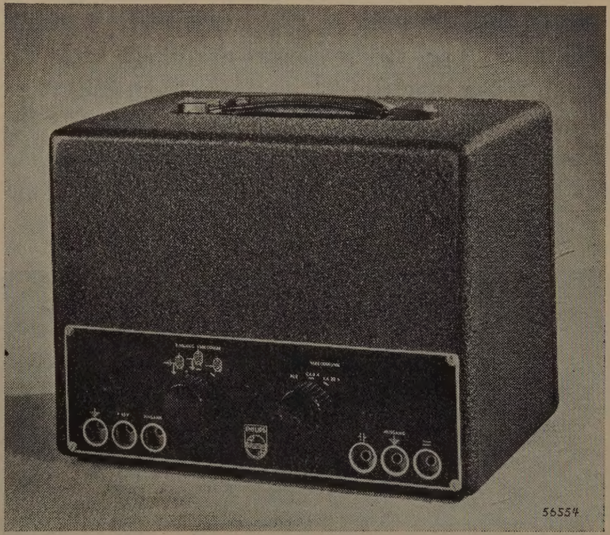

Fig. 8. The pre-amplifier GM 4570, which is suitable for the arrangement according to fig. 7. Gain 4 times or 20 times.

As pre-amplifier use can be made of the unit illustrated in *fig. 8*.

The sensitivity of the oscillograph can be calibrated with a known alternating voltage.

Applications

The applications of strain gauges in engineering can be divided into direct and indirect applications. Under the former are to be understood cases where strain gauges are used for measuring stresses in all sorts of mechanical constructions, whereas indirect applications cover their use with accessory apparatus required for taking various measurements.

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[3]) See e.g. Philips Techn. Rev. 7, 86, fig. 6, 1942.

[4]) S. L. de Bruin and C. Dorsman, A cathode-ray oscillograph for use in tool making Philips Techn. Rev. 5, 277-285, 1940.

[5]) See e.g. E. E. Carpentier, An electronic switch with variable commutating frequency, Philips Techn. Rev. 9, 340-346, 1947.

Direct applications

An extensive field for the use of strain gauges lies in the measuring of stresses in bridges, cranes, ships, aircraft, rolling mills, etc. As remarked in the introduction, better knowledge of the stresses occurring leads to more rational constructions with more reasonable margins of safety.

Of the numerous examples of the successful direct application of strain gauges we shall mention here only three.

In the first place there are the measurements taken on the hull of a ship at the time of launching, when a very complicated state of stress may occur. In order to measure the changes taking place in the stresses at a certain point of the ship's hull three strain gauges are applied at that spot close together at angles of 120°. The state of stress can then be easily calculated from the resistance variations of the three gauges.

A second example is the measuring of torque in a shaft. Two strain gauges are glued onto the shaft with an angle of 90° between them and at an angle of 45° with the centre line of the shaft (*fig. 9*). When torque arises one of the gauges is stretched and the other contracted. The torsion is calculated from the resistance variations of the two gauges.

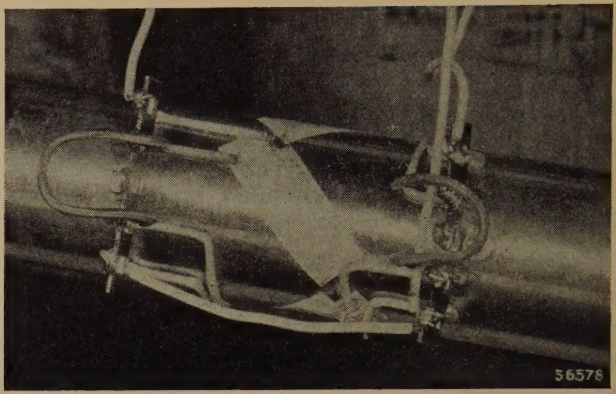
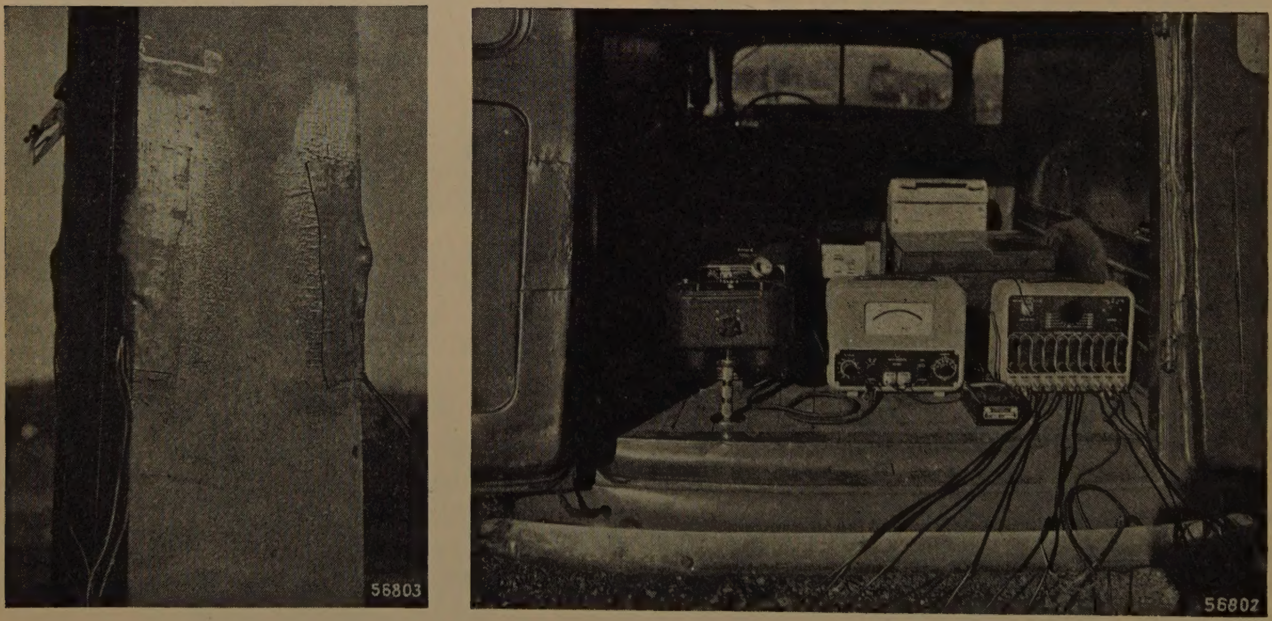


Fig. 9. Torsional vibrations in a shaft can be measured with two strain gauges at right angles to each other and making an angle of 45° with the centre line of the shaft. (In the experiment illustrated here four gauges were used, connected in parallel in pairs.)

As third example *fig. 10* shows the set-up used for measurements which were taken in cooperation with the Netherlands Railways to investigate the stresses arising in one of the arches carrying the overhead electric conductors in the event of rupture of the overhead line or the cable from which it is suspended. Strain gauges were glued onto one of the uprights at certain points and connected to a



a *b*

Fig. 10. *a*) Upright of an arch carrying the overhead power line of an electric railway, with four strain gauges for measuring the static load variations arising in the upright in the event of rupture of the overhead cable. Two of the strain gauges undergoing variations in length in the opposite sense to each other form a pair. They are complementary to each other as regards the elongation to be measured, but mutually compensate the effect of temperature variations. In order to exclude moisture the strain gauges are covered with a sheet of rubber enclosing a quantity of silica gel.

b) For measuring vibrations the strain gauges glued onto the upright could also be connected to a measuring bridge for dynamic loads. In the back of the car are to be seen from right to left the measuring bridge (GM 5536,) the circuit-selecting unit (GM 5545) and the oscillograph with camera set up in front of it.

measuring bridge GM 5536 (fig. 6). Upon the overhead power line being cut through, vibrations are set up which modulate the output voltage of the bridge, as may be seen from the oscillogram in *fig. 11*. From the measured amplitude it was deduced that at the point where the strain gauge was applied stresses occurred amounting to 600 kg/cm²; for further details see the caption of fig. 11.

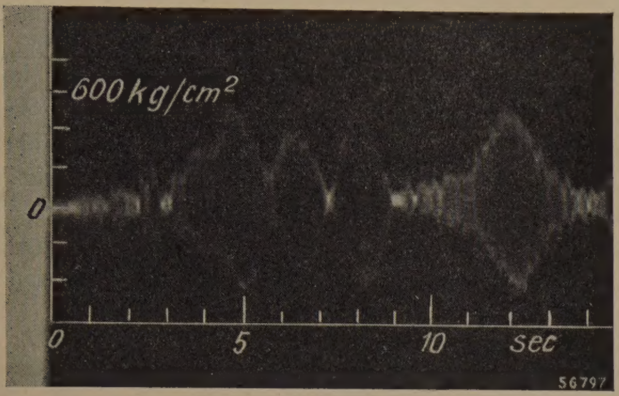


Fig. 11. Oscillogram (produced with the apparatus illustrated in fig. 10*b*) of the stress arising in the arch upright when the overhead power line is cut through close to the upright. This sets up vibrations which are propagated along the power line and the carrier cable and which are reflected partly in the next suspension points. This oscillogram gives a picture of the resultant interferences. The highest peak corresponds to a stress of about 600 kg/cm² at the point where the strain gauges are applied.

Indirect applications

Of the indirect applications of strain gauges we shall likewise confine ourselves to only a few examples which, in so far as they lie in the field of mechanics, concern apparatus developed by the "T.N.O." (Delft).

The ground-pressure and ground-water-pressure meters so far used have the drawback, among others, that they need a long adjustment time and often do not give any high degree of accuracy. Strain gauges provide a great improvement in this respect. The ground pressure or water pressure is transmitted to a diaphragm onto which a strain gauge has been fixed. The extent to which the diaphragm gives is a measure of the pressure, which can be made directly readable without any noticeable inertia and with a high degree of accuracy.

In *fig. 12* a dynamometer is illustrated with which forces of 1 to 10 tons can be accurately measured. The force to be measured is transmitted to a steel ring to which strain gauges have been applied for determining the elongation. A calibrating table gives the force as a function of the elongation measured.

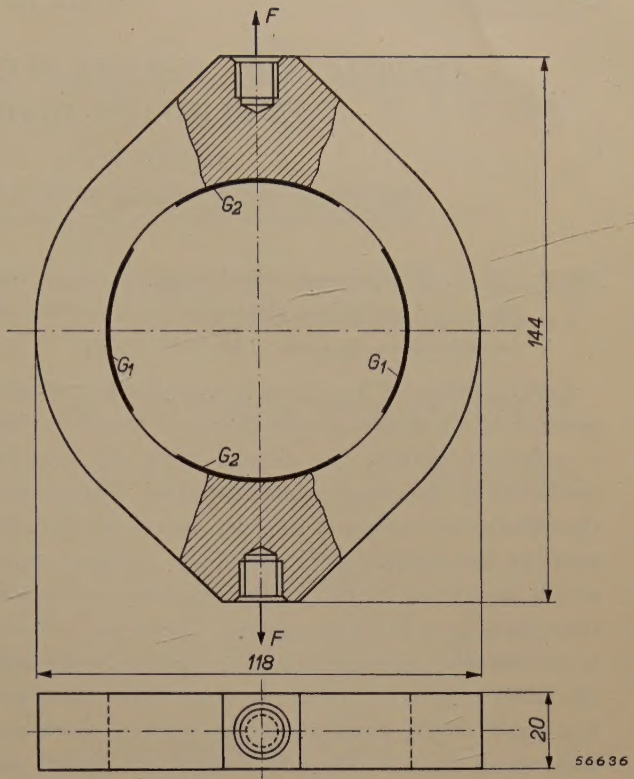


Fig. 12. Dynamometer (force meter) consisting of a steel ring which is elongated or contracted by the force F to be measured. The deformation of the ring is a measure of the force. It is measured by means of the two active strain gauges G_1. The gauges G_2 provide for temperature compensation and also act somewhat in the active sense since they change in length in the opposite sense to that of G_1. The dimensions given are in millimetres.

As last example we would mention an entirely different field of application, namely physiology, where strain gauges are used for oscillographing the heart beat, respiration and suchlike [6]).

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[6]) See e. g. H. R. Bierman, A device for measuring physiologic phenomena, using the bonded electrical wire resistance strain gauge, Rev. sci. Instr. **19**, 707-710, 1948 (No. 10).

Summary. Strain gauges are being used more and more as a means for determining changes in length. In their present form they consist of a wire bent in zig-zag fashion and glued onto a paper-carrier. The two types manufactured by Philips are 5.5 cm and 3 cm long (GM 4472, 600 ohms, and GM 4473, 120 ohms). The wire is of constantan, which has a constant gauge factor k (about 2.1), i.e. the ratio of the resistance variation to the elongation. The glue used for fixing the wire onto the carrier and the latter onto the workpiece is a strongly polar cellulose glue with great adhesive strength and showing very little "creep". This glue is sold in tubes. Two measuring bridges are described for determining the resistance variations: one for static loads only and the other for dynamic loads (vibrations) as well. Both are suitable for applying a second, compensating strain gauge for neutralizing the effect of temperature. This temperature compensation is not needed when only vibrations are to be measured; one strain gauge, a pre-amplifier and an oscillograph are then sufficient. The frequency range of the vibrations to which a strain gauge can respond extends to over 10,000 c/s. Finally a number of applications are discussed, both indirect (with force meters, pressure meters and suchlike) and direct, for determining the mechanical stresses in all sorts of constructional elements, particularly where other measuring methods are made impossible owing to the presence of vibrations or to inaccessibility.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk can be obtained free of charge from the address printed on the back cover.

1810*: J. L. Meijering: Hardening of metals by internal oxidation (Physical Society, Bristol Conference Report, 140-151, 1948).

Certain alloys of Ag, Cu and Ni with a few atomic percent of a homogeneously dissolved metal having a sufficient affinity for oxygen (Mg, Al) can be hardened by diffusing oxygen into them. The greater the affinity for oxygen of the basis metal, the greater must be the affinity of the solute to produce oxide which is not too coarse, as the conglomeration will take place by way of the atoms. This is worked out in a tentative thermodynamic scheme. X-ray and electrical resistivity measurements show that the MgO and Al_2O_3 particles which harden silver are very small indeed. The mechanical properties are not much affected by long annealing, especially when the dissolved free oxygen is not removed after the oxidation. Recrystallization is slowed down considerably. A drawback is the intercrystalline brittleness of these materials, which is less serious when somewhat smaller hardnesses are aimed at; single crystals are completely ductile. In some alloys complications arise at higher concentrations from the formation of inner oxide films, which slow down the penetration of oxygen (See Philips Res. Rep. **2**, 81-102 and 260-280, 1947).

1811: R. Vermeulen: Melodic scales (J. Acoust. Soc. Amer. **20**, 545-549, 1948, No. 4).

In this article an attempt is made to give a derivation of musical scales on a melodic rather than harmonic principle. Starting from the hypothesis that the scale shall contain, at most, two different intervals and shall contain a reasonably perfect fifth, all possible scales have been investigated. The customary scale appears here in the form of the Pythagorean scale. Apart from this certain other possibilities are found, which partly coincide with other existing scales.

1812: J. M. Stevels: Some chemical aspects of opacification of vitreous enamels (J. Sheet Metal Industries **25**, 2234-2237, 2240, 1948).

A vitreous enamel generally consists of a vitreous phase in which another phase is dispersed. For this reason vitreous enamels show opacification. The dispersed phase may be formed: 1) by crystals formed from the melt (devitrification; not used in practice), 2) by introduction of crystals insoluble in the melt into the batch, 3) by two unmixible vitreous phases. The influence on the opacification of particle size and particle shape is discussed extensively. Finally the influence of the chemical composition of the vitreous and the dispersed phase is discussed.

1813: H. B. C. Casimir: On the attraction between two perfectly conducting plates (Proc. Kon. Ned. Akad. Wetensch. Amsterdam **51**, 793-795, 1948, No. 7).

It is proved that between two parallel metallic plates an attractive force exists, which is independent of the material of the plates as long as the distance is such that for waves of a wavelength comparable with the distance the depth of penetration is small compared with the distance. This force may be interpreted as a (negative) pressure due to the zero point energy of electromagnetic waves. Similar effects come to the fore in calculating the influence of retardation on the Van der Waals-London attraction between two atoms (see these abstracts, No. **1793**).

1814: C. J. Bouwkamp: A note on Mathieu functions (Proc. Kon. Ned. Akad. Wetensch. Amsterdam **51**, 891-893, 1948, No. 7).

A short proof of the theorem stating that the Mathieu equation $y'' + (a - 2q\cos 2z)\, y = 0$ does not possess two linearly independent periodic solutions of period 2π, unless $q = 0$ and $a = n^2$ (n integer). A conjecture of Mac Lachlan relating to the characteristic values for imaginary q is disproved.

1815: K. F. Niessen: Nodal planes in a perturbed cavity resonator, I (Appl. sci. Res. 's-Gravenhage, **B1**, 187-194, 1948, No. 3).

In this paper a cavity resonator is considered which is generated from a prismatic cavity with square cross section by rotation of one of the walls through a small angle δ about its edge. The electric field is supposed to be parallel to that edge. The change in resonance frequency and the distortion of the electromagnetic field due to the perturbation are calculated.